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FABRICATION AND TEST OF A FLUERIC POSITION SERVO

by

M.H. Cardon and R.H. McFall

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

by

BENDIX RESEARCH LABORATORIES
Southfield, Michigan

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Final Report

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15 August 1968

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FABRICATION AND TEST
OF A FLUERIC POSITION SERVO

By

M. H. Cardon and R. H. McFall

ABSTRACT

A flueric position servo has been designed to position a control drum of a nuclear rocket engine. The flueric amplifier of the servo, which is implemented with vortex elements, was evaluated experimentally. The system uses a piston-cylinder with a rack and pinion that produces 180 degrees rotary output. The system is designed to have a 6 hertz bandwidth, 0.2 degree of resolution, and 300 in-lb stall torque. The supply pressure is 215 psia and the exhaust pressure is 50 psia. This report describes the system and presents the results of the experimental evaluation performed on the components.

SECTION 1
INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

This report details the results of a second of two tasks performed in the development of a pneumatic actuation system which employs fluerics in lieu of electronics. The objective of Task II was to fabricate and evaluate the system designed in the Task I program. Overall requirements called for design, development and evaluation of a system that would: replace electronics in an existing AG-20 Actuating System; and operate, without shielding, in a specified radiation environment.

Essentially, the actuator system described herein employs flueric devices for error detection, dynamic compensation and amplification. The purpose of using fluerics in place of electronics is to permit the closing of position control loop at the actuator-motor location. In so doing, the number of electrical components and connections exposed to the actuator-motor environment is minimized, thereby increasing reliability. By virtue of superior environmental tolerance, the pneumomechanical circuits can be used in a nuclear radiation environment where unshielded electronic circuitry cannot.

The advantage of fluerics stems from two noteworthy considerations. First, the orifices, channels, and chambers can be made of stable materials that are relatively unaffected by nuclear radiation and temperature extremes. Second, summing and amplification can be performed without the use of mechanical moving parts. By properly directing fluid streams (through orifices, connecting channels and chambers), interaction of these streams provides the desired operational characteristics.

An already existing control drum actuation system for a nuclear rocket engine and its specification and requirements were prescribed for this development. Figure 1-1 shows a block diagram of the pneumatic control system. The actuator-motor has two pistons mounted on opposite ends of a short, rack-driven pinion gear. This pinion gear is coupled directly to the load, of the actuation system, which consists of a control drum with friction and inertia, and a scram spring. Drum rotational travel has a minimum requirement of 180 degrees and a normal operating range of 15 to 165 degrees. Supply gas to this system is hydrogen at 215 psia and at temperatures ranging from 100°R to 600°R; exhaust pressure is 50 psia.

The results of Task I, design and analysis, are published in NASA Summary Report, CR-54758, "Replacement of Electronics with Fluid Interaction Devices." Results of Task II, fabrication, assembly and evaluation, are presented in this report.

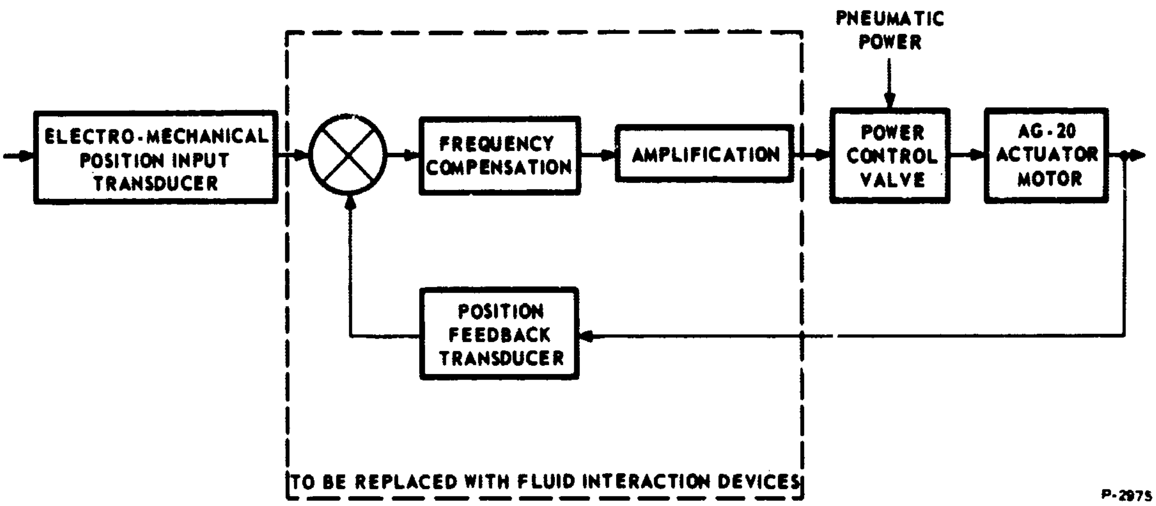


Figure 1-1 - Block Diagram of Pneumatic Control Drum Actuation System

Section 2 presents a review of compensation requirements and a general description of the flueric position servo. Section 3 discusses the mechanical configuration of the actuator and the design details of the error detector unit, power control valve, and flueric circuit. Section 4 is a detailed discussion of the flueric circuits and the results of the experimental tests. Included in Section 4 are the dynamic characteristics of the lead-lag circuit, and the static characteristics of the other network stages. A description of the vortex valves, amplifiers and summers, used in the flueric circuits are described in Section 5, along with a presentation of the experimentally determined performance characteristics.

The report conclusions and recommendations appear in Section 6.

1.2 SUMMARY

In this development the electronic network of the G.E. AG-20 control drum actuation system is replaced by a flueric amplifier network. The pneumatic actuation system (flueric position servo) consists of a position error detector unit, a flueric amplifier network, a power control valve, and the Model AG-20 actuator motor. The components of the servo were fabricated and the flueric amplifier network was experimentally evaluated.

The position error detector unit generates a pneumatic signal proportional to the difference between the command and the actual actuator positions. An electric command signal is converted by a flapper-nozzle controlled by a torque motor. The signal representing the actuator position is obtained from a flapper-nozzle that is driven by a cam connected directly to the actuator output shaft. The position error detector unit has been assembled. Adjustment and checkout have yet to be accomplished.

The flueric amplification network consists of vortex valves, vortex pressure amplifiers, and vortex summers operating in push-pull stages. The network has three main sections: the position error channel, the rate feedback channel, and the lead-lag circuit. Tested individually in breadboard setups, each section fulfilled the static performance requirements. The position error channel and the lead-lag circuit met both static and dynamic requirements. The signal-to-noise ratio was acceptable in the position error channel and lead-lag circuit but was excessive in the rate feedback channel.

The power control valve is a flapper-nozzle valve incorporating dynamic load pressure feedback that provides damping and low frequency lag-lead compensation to meet the steady-state resolution requirements. The flapper is actuated by a pair of bellows pressurized by the flueric amplification network. The power control valve has been assembled. Adjustment and checkout have yet to be accomplished.

Further development under Contract NAS3-6201 has stopped. However, the experimental evaluation performed on the components, in particular those of the lead-lag circuit, indicates that the performance goals can be achieved if the noise in the rate feedback channel is reduced.

SECTION 2

ACTUATION SYSTEM

In this section, compensation and amplification requirements, established in Task I, are reviewed and a general description of the flueric position servo is presented. In selecting the flueric components and circuits, paramount importance was placed on power, or gas, consumption. For this reason, vortex amplifiers were used in push-pull pairs with exit flows completely collected and used to control the next downstream pair. Small bleeds were used at these connections to trim the bias level of the stages; however, this flow was a very small percentage of the total flow. This technique of bleeding proves to be particularly advantageous in that bias levels could be adjusted with no detectable change in the pressure gain of the stage. To date, the vortex amplifier has proven to be the only flueric amplifier which can be successfully connected in series with a following stage, without resorting to appreciable venting. Vortex amplifiers as referred to in this report include two types: the vortex valve, a flow amplifier; and the vortex pressure amplifier which uses a vortex valve in conjunction with a pickoff or receiver orifice in the path of the exit flow of the valve. The amplifiers are described in detail in Section 5.

2.1 AMPLIFICATION AND COMPENSATION REQUIREMENTS

2.1.1 System Gain

The overall position loop gain was established at a level which would insure that the actuator would meet the specified threshold levels. In order to fully meet this requirement, i.e., establishment of a sufficiently high static stiffness, while at the same time providing proper damping and bandpass for the control system, it was necessary to use positive pressure load feedback at low frequencies to offset the negative load pressure feedback required for damping at the resonant frequency of the actuator.

The proper level of negative pressure feedback is provided by the action of the load differential pressure bearing on the flapper of the power valve. The proper magnitude of the negative pressure feedback is established by designing the nozzle areas of the power control valve to the proper size. The load differential pressure is also fed to a differential bellows actuator through a low pass filter, so that the negative pressure feedback is cancelled at low frequencies, to provide the high static stiffness required. The low pass filter used consists of an orifice placed in series with the bellows. The volume in the bellows acts as a capacitance to inhibit high frequency load pressure variations from being fed back. Another pair of differential bellows is

used at the flapper to provide the signal input from the flueric amplifier.

These power valve connections are shown in schematic form in Figure 2-1.

2.1.2 System Bandpass

The large volume under compression in the piston cylinder actuator limits the open-loop natural frequency of the actuator and, therefore, the neutral stability resonant frequency of the system. System bandpass is characterized by the neutral-stability, resonant frequency, which is the frequency at which the closed-loop phase shift is 180 degrees and the frequency at which the amplitude response begins to fall off rapidly. With the gain margin set at -6 db, the closed-loop amplitude ratio is unity if the system characteristic is cubic.

It is known that error rate compensation or rate feedback compensation will increase the neutral-stability,resonant frequency of the system. Since rate limiting was required, the rate feedback used for rate limiting assists in increasing the bandpass. In the practical flueric rate feedback circuit some lag occurs and, therefore, it was necessary to use error rate compensation as well — to achieve the required bandpass or neutral stability resonant frequency.

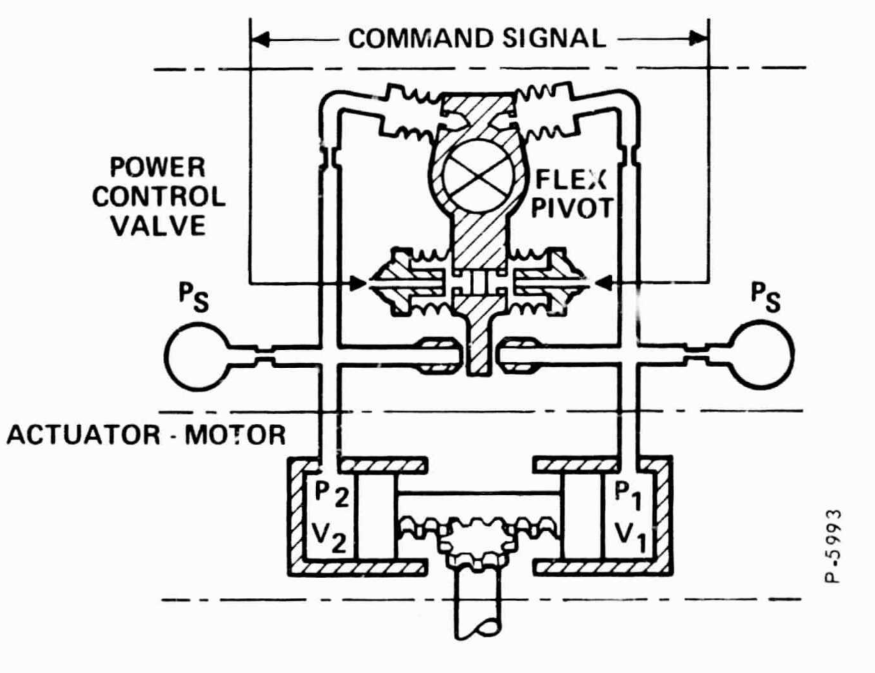


Figure 2-1 - Schematic of Valve and Actuator

The block diagram of the system is shown in Figure 2-2. Rate feedback is shown as the block having rate gain K_R. Lead or error rate compensation is achieved by feeding back the output of the final stage of the flueric amplifier, through a low pass filter, to an upstream amplifier stage. This circuit is represented by the path containing the gain term K_2,

2.1.3 Rate Limiting

In order to provide a rate limit, i.e., a limited maximum slew rate of the actuator, a saturating amplifier stage is used in the position error channel so that the maximum error signal is limited to a specified value. This limited value of error signal is compared against the rate signal from the rate feedback channel and, as long as the positioning error signal is on the limit, the servo is a rate servo slewing at the designed output rate. As the position error becomes less than the limit value, the rate of the output motion decreases until the servo nulls with respect to the commanded position. Since the practical flueric rate circuit has a time lag, τ_2 sec, it is necessary to use a lag in the position channel, τ_1, to offset the overshoot which would otherwise result when the servo entered the rate limiting zone of operation. The delay, τ_1, need not be set exactly equal to τ_2; in fact, it can be slightly smaller, thus, providing some lead-lag compensation for the position loop when it is not in the rate limit mode. The time lags, τ_1 and τ_2, and the saturation block are shown in the schematic, Figure 2-1.

The computer analysis used to determine the proper gains and time constants is reported in the final report for task 1, NASA Report No. CR-54758, dated August 31, 1965.

2.2 DESCRIPTION OF THE POSITION SERVO

A schematic diagram of the flueric position servo is shown in Figure 2-3, and a photograph of the position servo and its load fixture

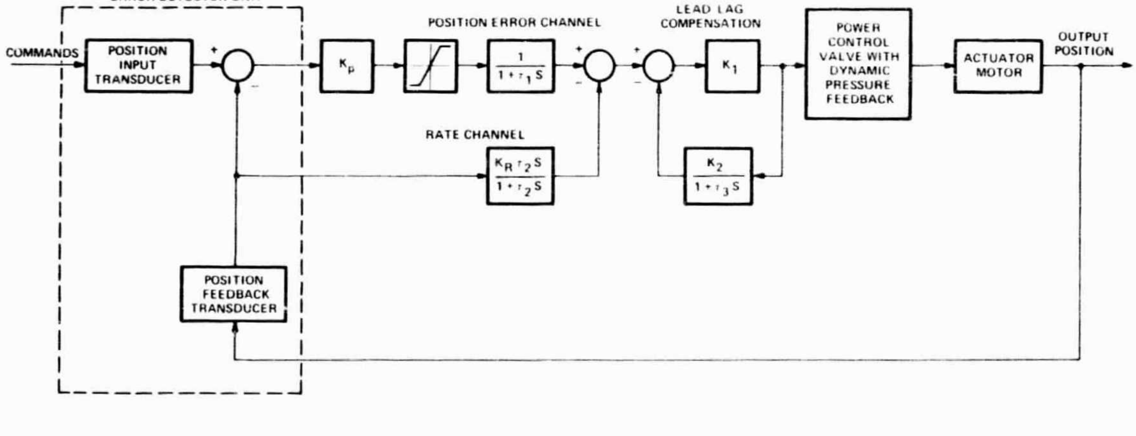


Figure 2-2 - Block Diagram of the Fluidic Control Drum Actuation System

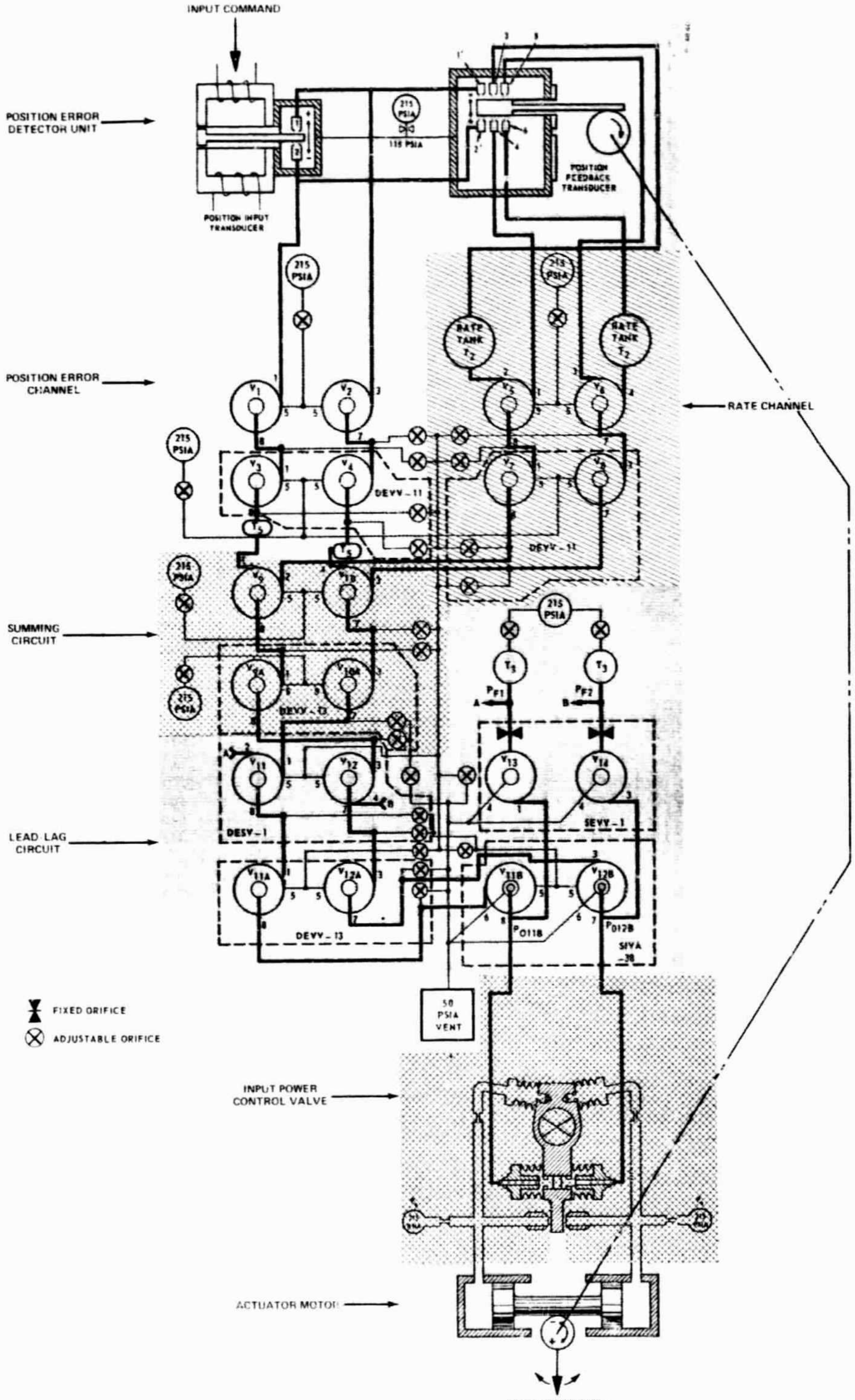


Figure 2-3 - Schematic Diagram of the Flueric Position Servo

is shown in Figure 2-4. The servo consists of a position error detector unit, position error and rate channels, summing circuit, lead-lag circuit, input power control valve, and actuator motor.

The position error detector unit, in conjunction with the control orifices of first stages of the position and rate channels, generates position error and velocity signals. The input to the position error detector unit is an electrical position command signal which is transduced to an equivalent torque motor flapper position between two in-flowing nozzles. The actuator position is transduced to an equivalent position of a flapper between two in-flowing nozzles of the same size and spacing as those of the input command. The flapper is actuated by a cam coupled directly to the output shaft of the actuator. When the area of respective in-flowing nozzles differ, a differential pressure signal is generated.

The position signal is amplified and limited in the position error channel. Limiting is achieved through the saturation characteristic of the second-stage vortex amplifiers. From the position error channel, the position signal goes to the summing circuit where it is summed with the rate signal and then amplified. This amplified signal then goes to the lead-lag circuit where additional amplification and dynamic compensation of the signal are achieved. The output of the lead-lag circuit is the input to the power control valve. The power control valve uses the flapper-nozzle principle and incorporates dynamic pressure feedback.

The rate signal is generated by differentiating a position signal using volumes and orifices. In the flueric circuit, the amplification and summing function are performed by vortex pressure amplifiers, valves, and summers. These elements are constructed in push-pull pairs and have a chamber diameter of 0.140 inch and an exit orifice area of 0.020 inch. The flueric circuit mounts directly on the AG-20 piston-type actuator, forming an integral closed-loop servo requiring only an electrical input command signal.

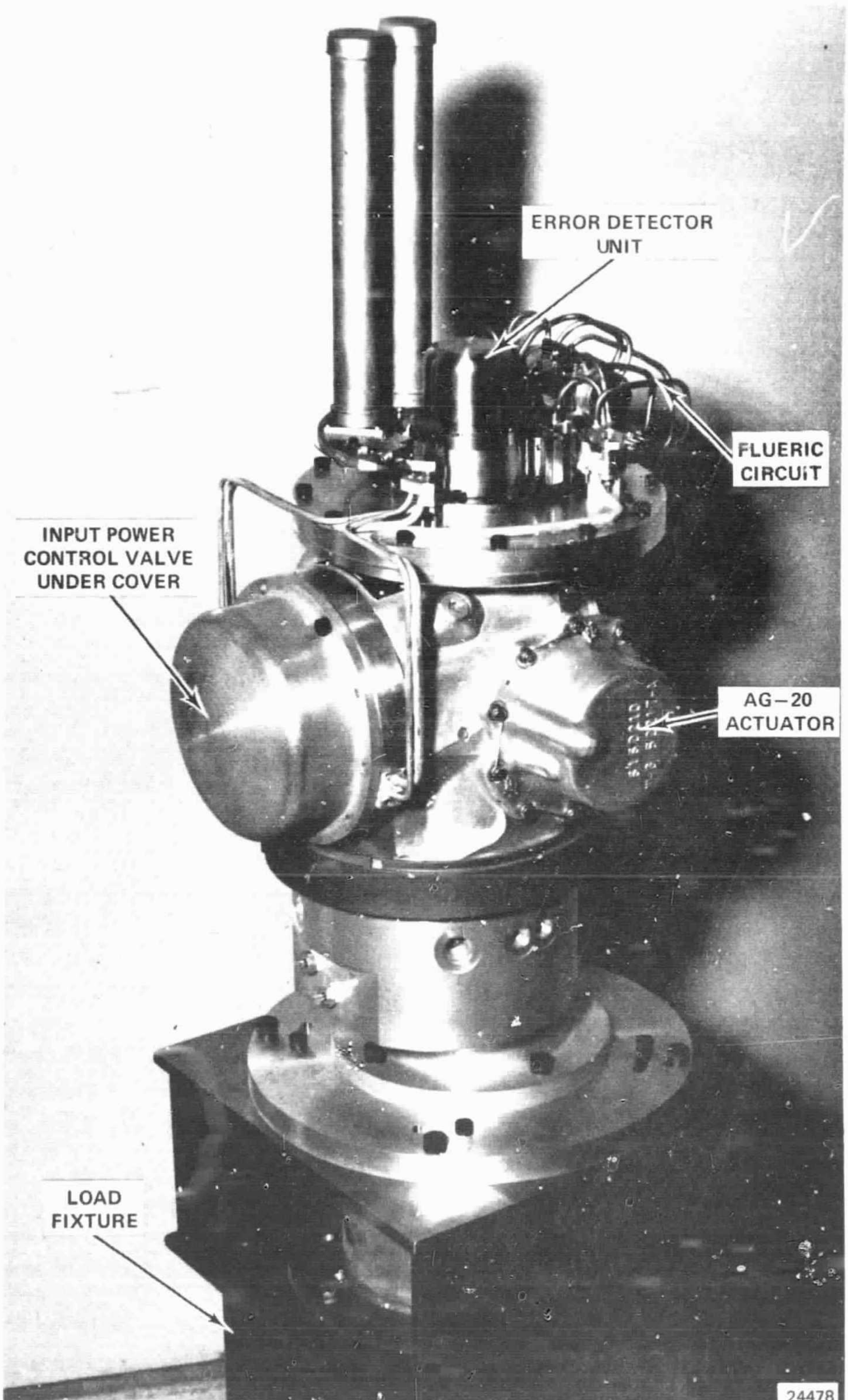


Figure 2-4 - Actuator Complete with Fluidic Control Circuit
Mounted on a Test Fixture

SECTION 3

MECHANICAL CONFIGURATION

This section describes the actuator and its load, the error detector unit, power control valve, and mechanical configuration of the flueric circuit.

The Flueric Position Servo assembly is shown in Figure 3-1. In this configuration, the AG-20 actuator forms the basic structure. The flueric amplifier and compensation network, and the error detector unit, are mounted on an adapter plate. This adapter plate is bolted directly to the actuator in place of the housing that formerly covered the potentiometers. The error detector unit is coupled directly to the former potentiometer drive.

The power control valve is mounted on a sub-plate that communicates the power control valve with the original valve supply and load ports, and the supply gas and exhaust of the actuator with the flueric circuit.

3.1 AG-20 ACTUATOR AND LOAD

The AG-20 actuator-motor is a piston-cylinder device in which the linear motion of the piston is converted to a rotary motion by the means of rack and pinion. The load consists of the control drum, its associated friction, and a scram spring.

The power control valve, the AG-20 actuator-motor, and the load are illustrated in Figure 3-2. The power control valve is a flapper-nozzle valve which has dynamic load pressure feedback. This valve is discussed in detail in subsequent paragraphs and is shown here only to help illustrate how the actuator-motor functions.

The actuator-motor has two separate pistons which are mounted on opposite ends of a short rack. The rack drives a pinion gear that is coupled directly to the load. The intermediate volume between the pistons is kept at a constant pressure which prevents any cross-port leakage between the cylinder chambers V_1 and V_2. In mid-position, each chamber has a volume of 4.36 cubic inches. The actuator-motor has a displacement, in terms of output shaft rotation, of 2.2 cubic inches per radian.

The load has a maximum rotation of 0 to 180 degrees and a working rotation of 15 to 165 degrees. The scram spring has a mid-position torque of 106.8 lb-in and a spring rate of 24.3 lb-in per radian. The spring force acts to reduce the angle of rotation of the load. The control drum has a polar moment of inertia of 0.24 in-lb-sec^2. The static friction load is 54 lb-in and the dynamic friction load is 47 lb-in.

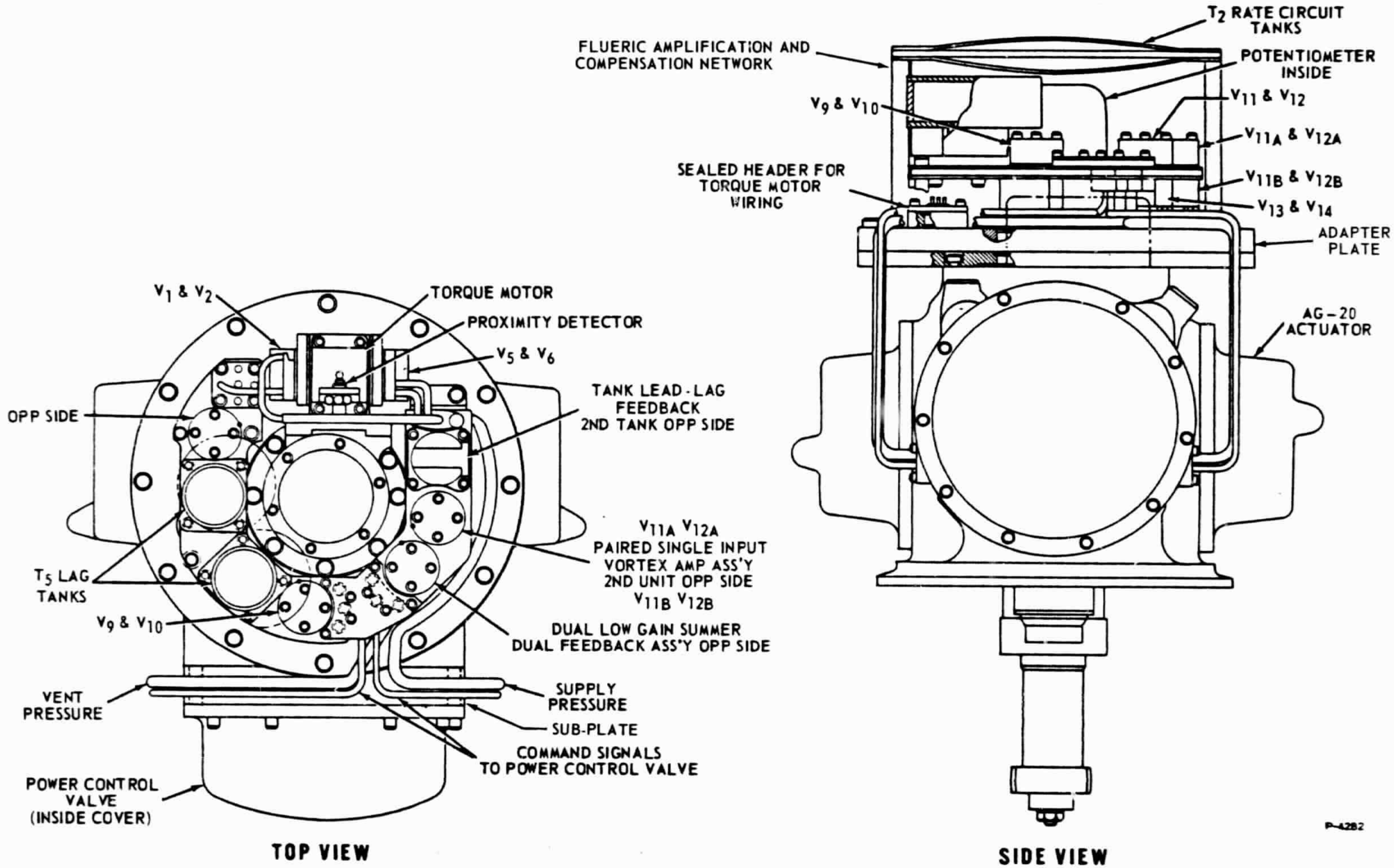


Figure 3-1 - Assembly - Modified AG-20 Actuator with Flueric Position Servo

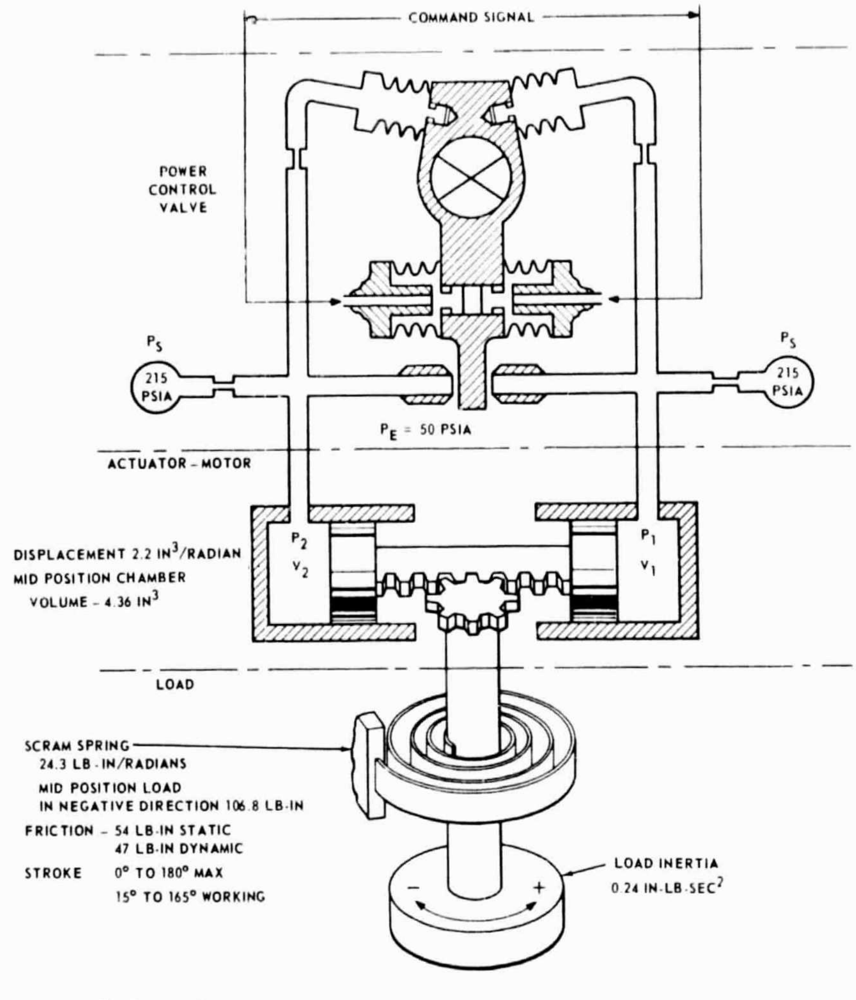


Figure 3-2 - Schematic of Valve, Actuator Motor and Load

A drawing of the actuator test fixture, incorporating the scram spring and a simulated load, is shown in Figure 3-3.

3.2 POSITION ERROR DETECTOR UNIT

The assembly drawing of the Position Error Detector Unit is shown in Figure 3-4; its schematic is shown in Figure 3-5.

The Position Error Detector Unit comprises a position input transducer and a position feedback transducer that generate signals independently for both position and rate feedback. For convenience, it also includes a potentiometer for instrumenting the position of the actuator output shaft. A modified D.G. O'Brien, Model 121, torque motor is used in the position-input transducer. The coils of the torque motor have a resistance of 100 ohms per coil and require a maximum input differential

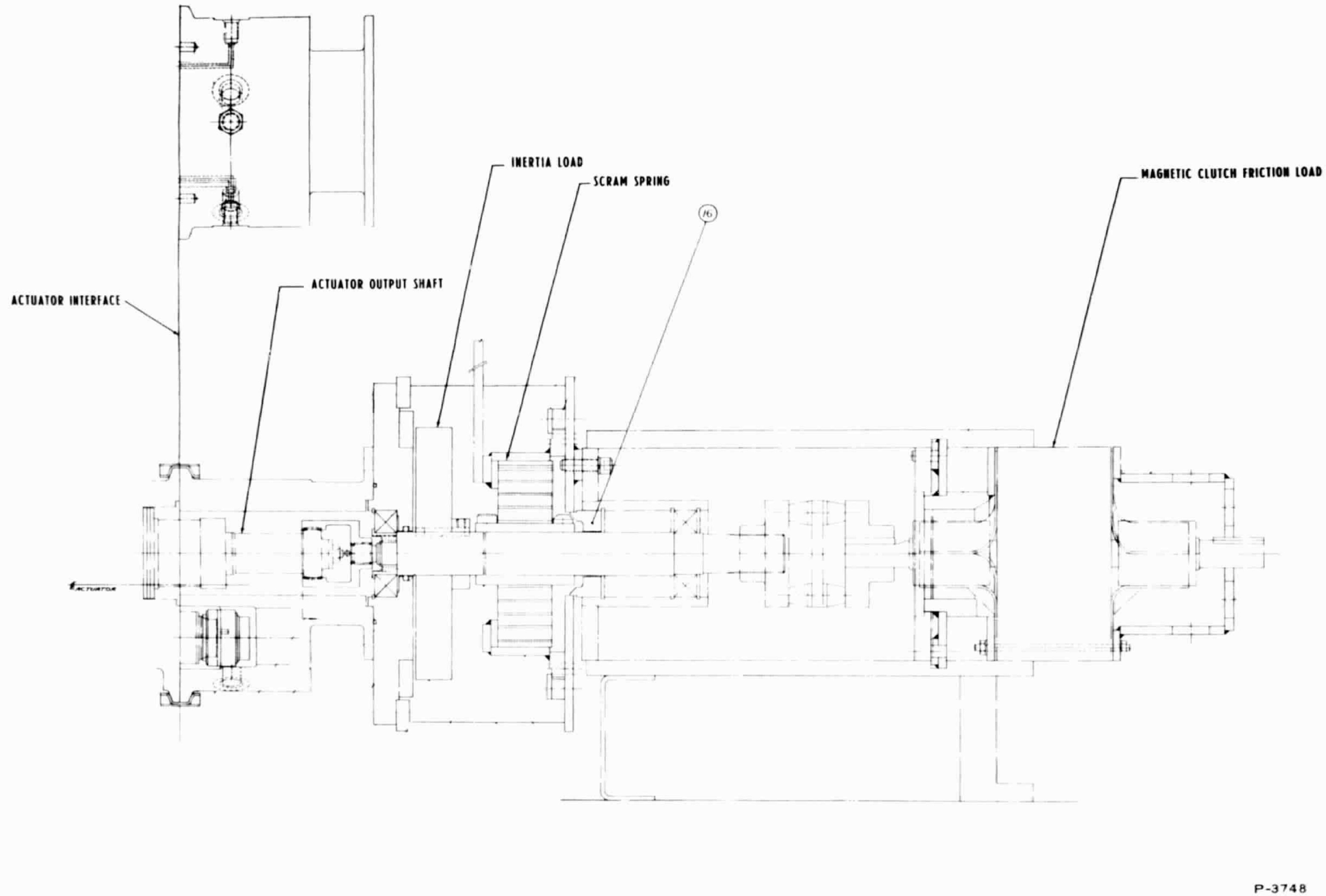
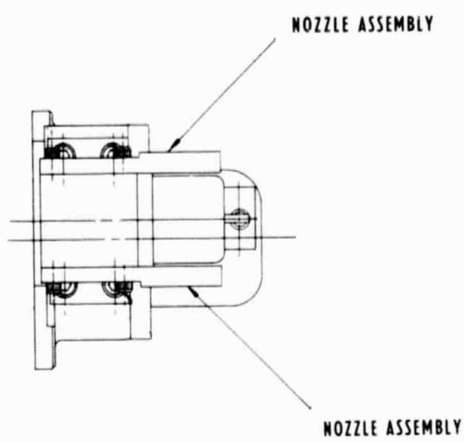


Figure 3-3 - Actuator Test Fixture



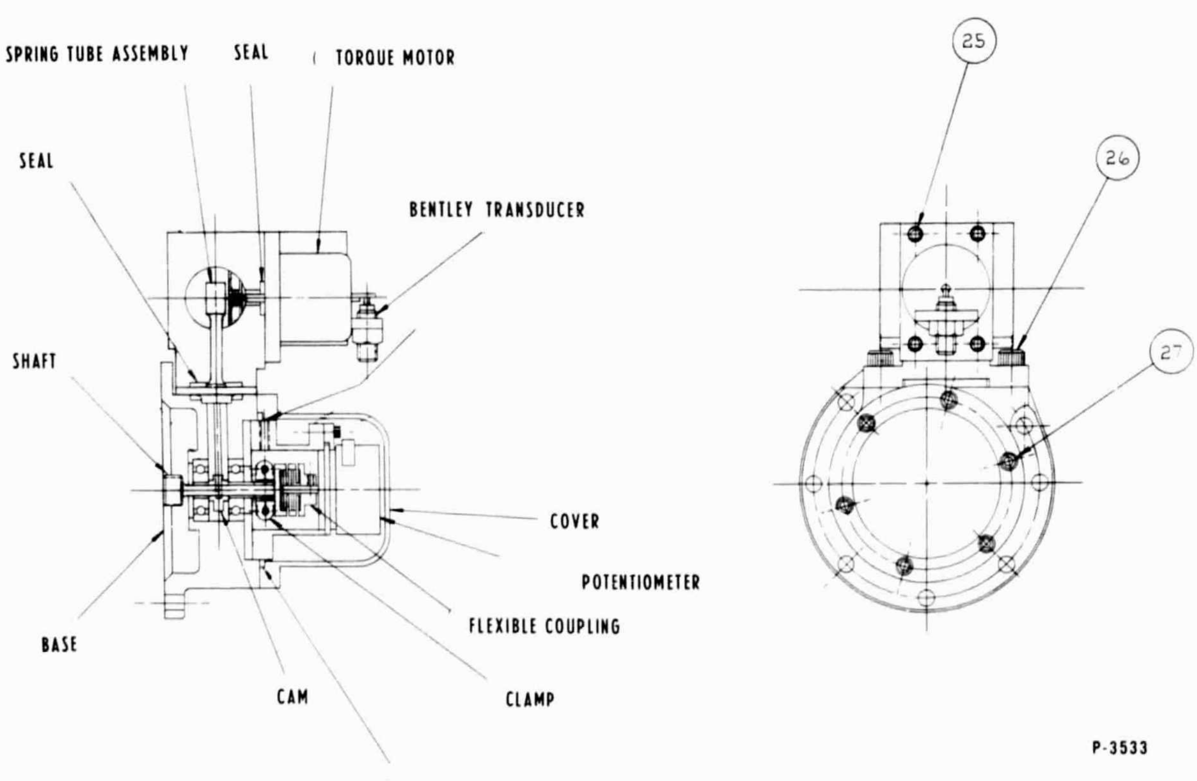


Figure 3-4 - Position Error Detector Unit

current of 150 ma. Modifications to the torque motor included an extension of its flapper out through its case and the addition of a bracket on the case for mounting a Bentley HI-084-3 proximity transducer. The proximity transducer will be used, during evaluation tests, to indicate the position of the flapper of the position input transducer.

In the position feedback transducer, a cam that is coupled directly to the output shaft of the actuator moves the flapper of the spring tube assembly between three pairs of nozzles. One pair of nozzles is used, in conjunction with the nozzles of the position input transducer, to generate the position error signal. These nozzles are the same size as the nozzles of the position input transducer. The other two pairs of nozzles are used in generating the rate signal.

The cam of the position feedback transducer is designed to have a total travel of 216 degrees of rotation as compared to a 180-degree stroke of the actuator. The additional travel of the cam allows some tolerance in setting up the nozzles with the flapper. Total displacement of the flapper at the cam, for the 216 degrees of rotation, is 0.1037 inch and results in a 0.0047-inch deflection at the nozzles. The deflection at the nozzles for 180-degree working stroke is 0.00392 inch. Contact force between the flapper and cam is 0.17 pound at the zero position of the actuator output shaft and 1.85 pounds at the 180-degree position.

The potentiometer incorporated into the Position Error Detector Unit is a Markite Model SL-111. It has a maximum resistance of 1000 ohms and a linearity of $\pm 0.5\%$.

In operation, an electrical command signal is converted to a torque motor flapper position. The flapper position of the position feedback transducer is proportional to actuator position. A displacement of the position input transducer flapper toward nozzle No. 1 causes a decrease in pressure in nozzle No. 1 and an increase in pressure in nozzle No. 2 These pressure changes are transmitted through the flueric circuit causing the actuator to move until the flapper in the position feedback transducer moves toward nozzle No. 2', returning the pressures in nozzles No. 1, 2, 1', and 2' to their original values. Reverse-flow flapper nozzles are used to conserve flow. Nozzles No. 3, 4, 5, and 6 sense actuator position to be used, to generate a velocity signal in the rate circuit.

The position error detector unit and flueric circuit components, V_1, V_2, V_5, and V_6 (refer to Figure 3-1) are shown in Figure 3-6.

3.3 POWER CONTROL VALVE

The Power Control Valve is a flapper-type valve incorporating dynamic load pressure feedback. The flapper of the valve is actuated by a pair of bellows, pressurized by a pneumatic input signal. A flapper-type valve inherently has negative load pressure feedback. The dynamic load pressure in this valve is achieved by positive feeding of the load

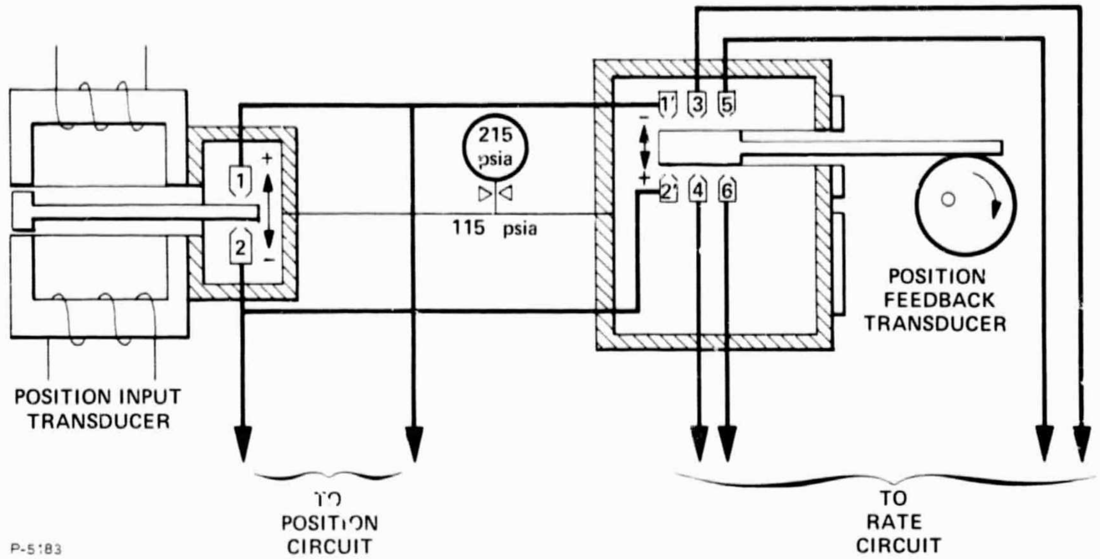


Figure 3-5 - Schematic Diagram of the Position Error Detector Unit

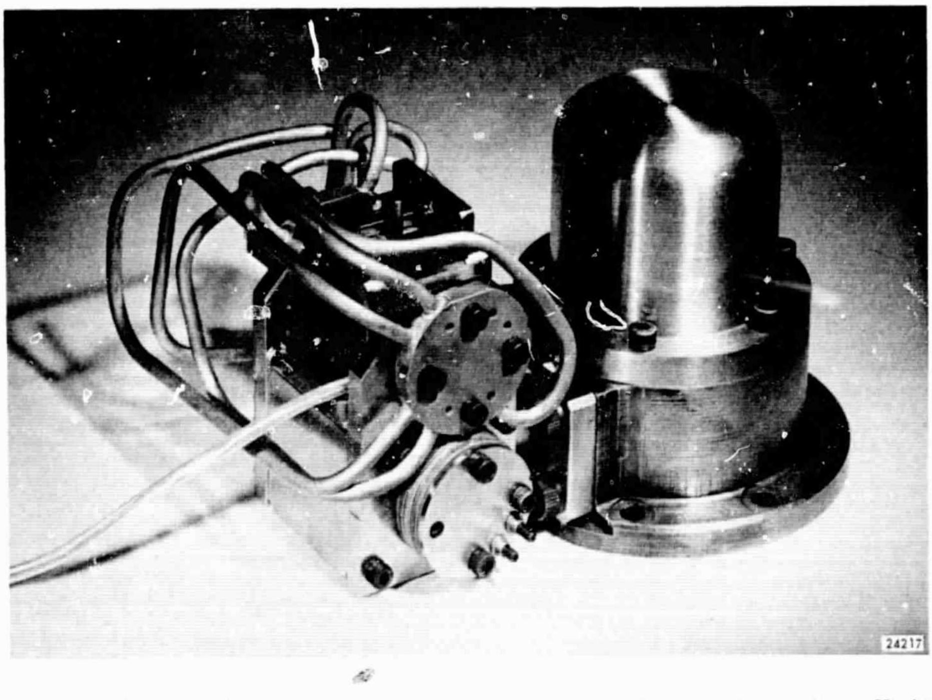


Figure 3-6 - Photograph of the Position Error Detector Unit

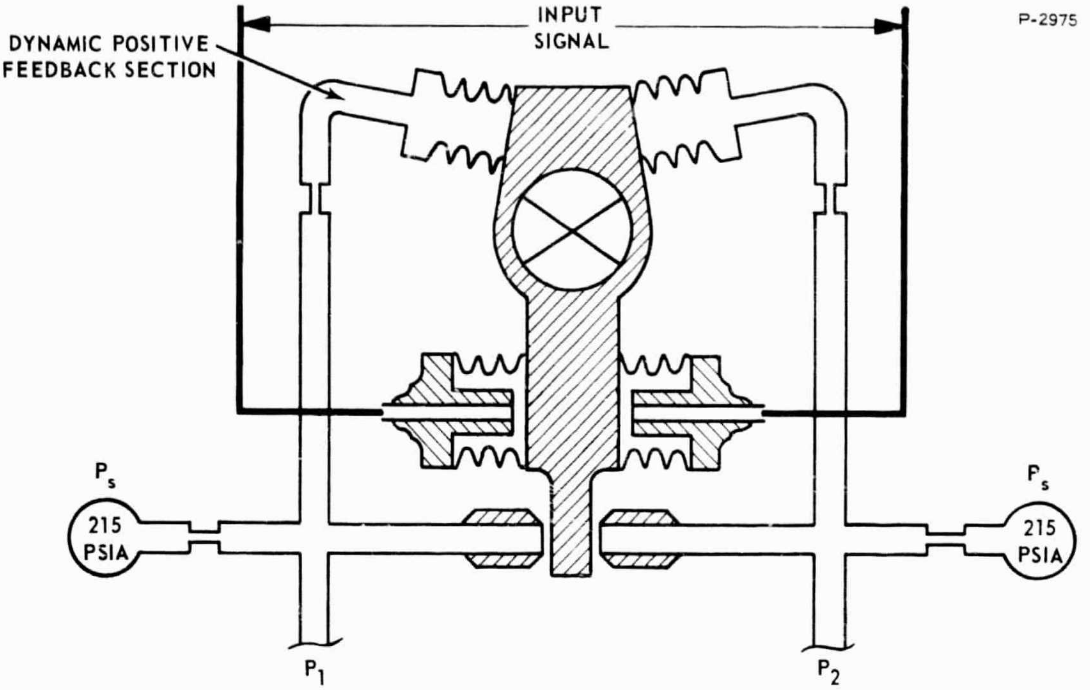


Figure 3-7 - Schematic Diagram of the Pneumatic Input Power Control Valve

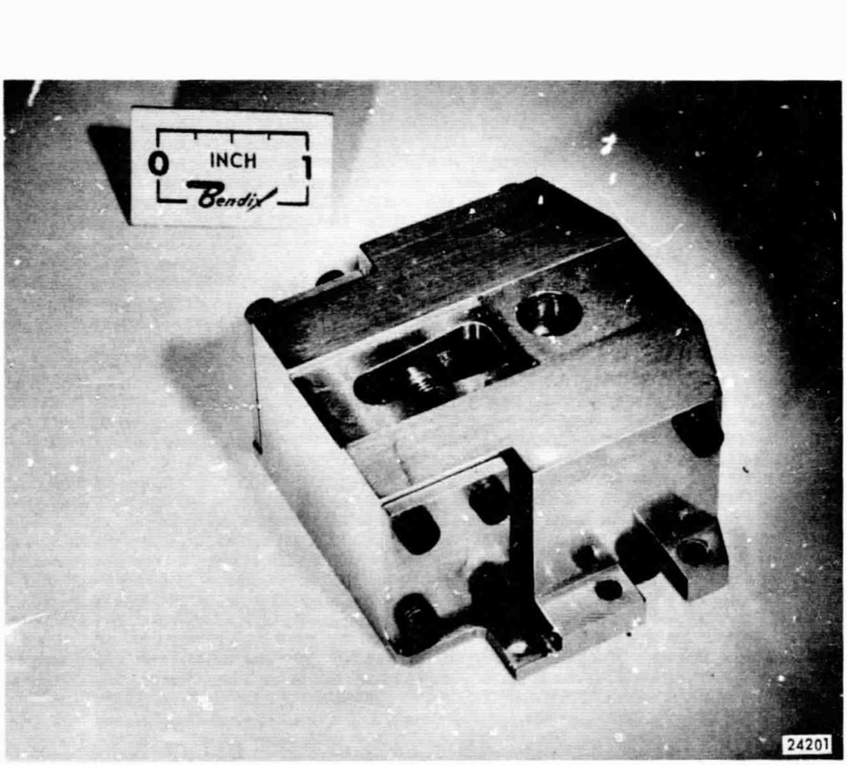


Figure 3-8 - Photograph of the Pneumatic Input Power Control Valve

pressures back, through an orifice volume network, to another pair of bellows acting on the flapper. A schematic of the power control valve is shown in Figure 3-7 and a photograph of the actual valve is shown in Figure 3-8. The valve is designed to have the following parameters:

Static Pressure Gain	=	12.8 psi/psi
Upstream Supply Orifice	=	0.0144 in^2
Maximum Downstream Orifice	=	0.047 in^2
Mean Downstream Orifice	=	0.0288 in^2
Undamped Natural Frequency of Flapper Assembly	=	1791 rad/sec

The predicted dynamic characteristics of the valve are shown in Figure 3-9.

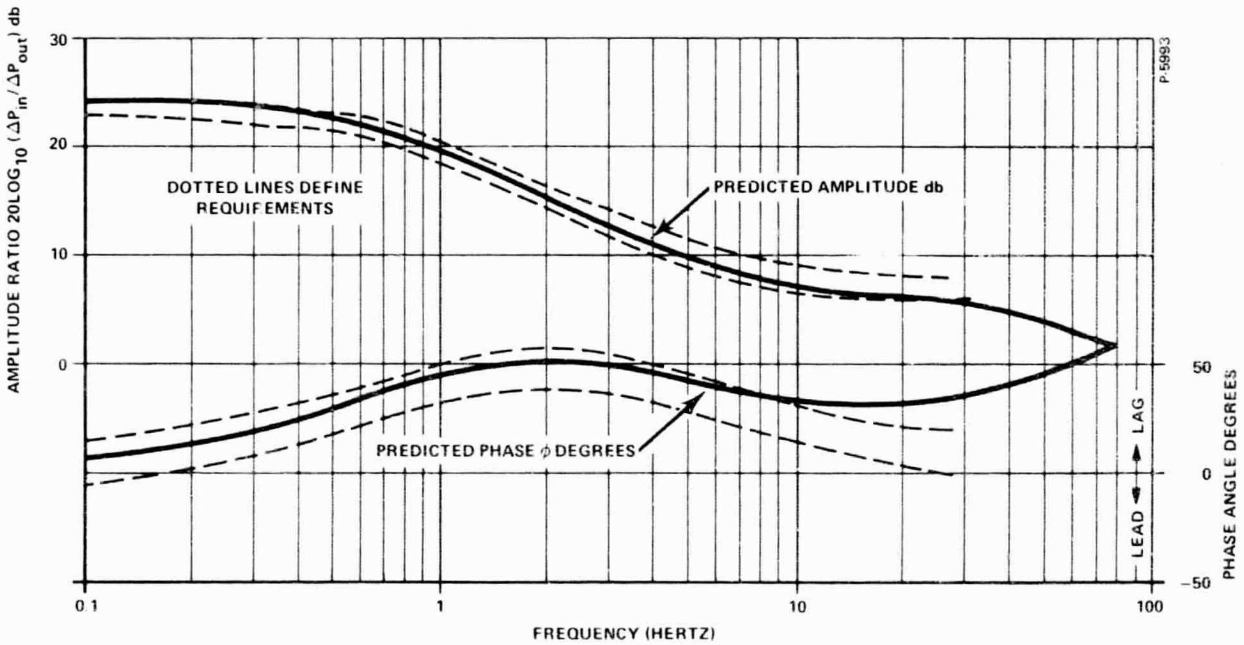


Figure 3-9 - Predicted Response of Power Control Valve, 600°R H_2

3.4 FLUERIC CIRCUIT

The fluidic circuit utilizes vortex pressure amplifiers, valves and summers, and passive elements such as orifices and volumes. The vortex elements are fabricated in push-pull pairs. These elements, along with the passive elements, are mounted on three different manifolds to form the flueric amplification and compensation network. The input valves, V_1, V_2, V_5, and V_6 of the position and rate channels are mounted on a manifold of the error detector unit (see Figure 3-6). Other elements of the position and rate channels, and summing circuit, are mounted on the manifold shown in Figure 3-10.

The lead-lag circuit has its own manifold and is shown in Figure 3-11. A complete flueric circuit, minus the input stages of the position and rate channels, is shown in Figure 3-12.

The manifolds are made up of a center section and two cover plates. The center sections have channels communicating the various components, and cover plates have the appropriate hole patterns for the components that fasten to it. Cover plates and center sections are made by conventional machining methods or built up of etched shim stock. In both cases, assembly is accomplished by diffusion-bonding with copper, the same as for the vortex components. A photograph of the manifold plates for the lead-lag circuit is shown in Figure 3-13.

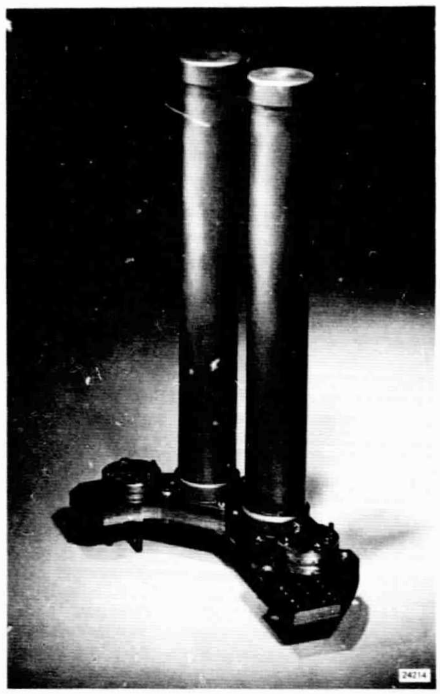


Figure 3-10 - Position Error, Rate, and Summing Circuit

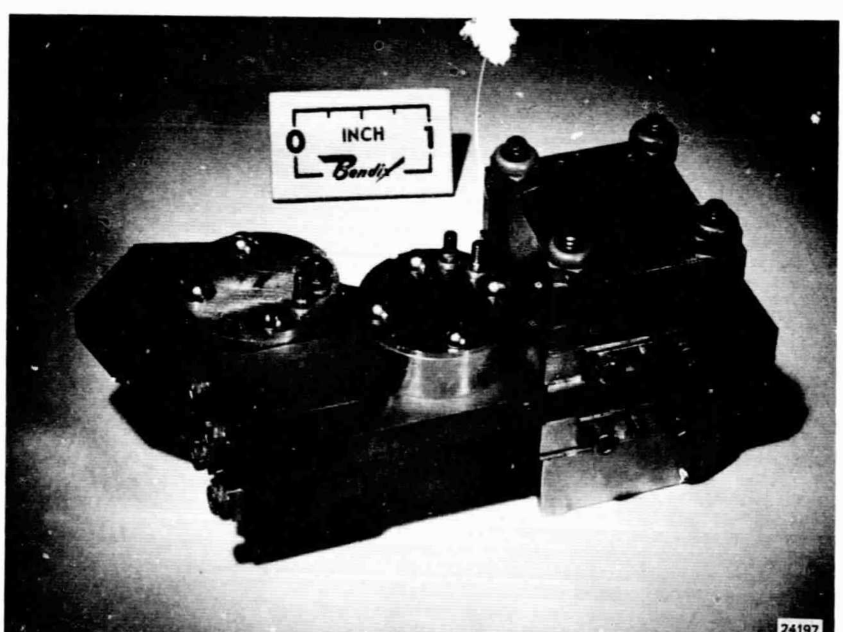


Figure 3-11 - Lead-Lag Circuit

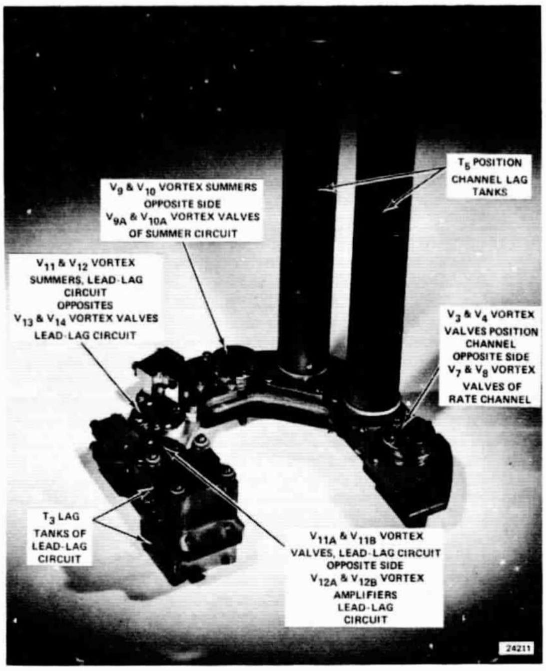


Figure 3-12 - Flueric Circuit

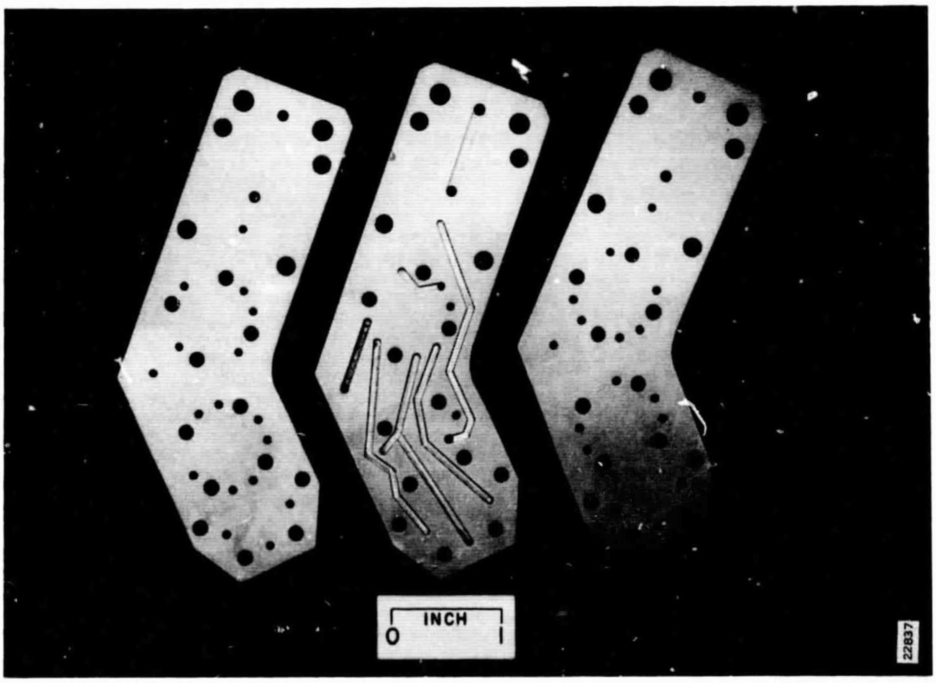


Figure 3-13 - Photo of Manifold Plate Components for Lead-Lag Circuit

SECTION 4

FLUERIC AMPLIFIER CIRCUIT

An overall schematic for the flueric amplifier circuit is shown in Figure 4-1. In selecting vortex amplifiers, serially cascaded to minimize gas consumption, care must be taken to properly match stages so that nearly all the flow can be collected by the following stages. If an improper match were used, wherein the upstream stages delivered too much quiescent flow to the downstream control ports, the excess flow would have to be vented in order to achieve proper operation. On the other hand, if the quiescent flows of the upstream stage were too small, proper bias levels could not be achieved at the following downstream stage without reducing the supply pressure to a level below that desired. Such pressure reductions would result in too low a pressure level at the final stage, thus preventing proper stroking of the power valve.

By building matched pairs of vortex amplifiers in a given stage of amplification and by designing them for the proper quiescent flows, the bleed flow required between stages to provide final matching and correct differential biasing was minimized. These techniques provided an amplifier design which resulted in a minimum total standby gas consumption, 0.0117 lb/sec.

In using push-pull vortex stages, all signals are summed on control ports which act in one geometric direction. By avoiding opposing control jets, all danger of having the bias swirl in a given amplifier change direction is eliminated.

Other features pertinent to the amplifier are well known, in that push-pull staging reduces sensitivity to supply pressure variations, temperature null shifts, and provides better linearity than is possible with a single-ended amplifier cascade.

As with most flueric amplifiers, a great deal of time and design effort was expended in achieving appropriate signal-to-noise ratios. Invariably, a very high gain stage is more susceptible to generating noise; reductions in gain were needed to reduce noise while finding the optimum signal-to-noise ratio. In general, noise was improved by using short length vortex chambers and well-finished exit hole entrance conditions.

In reducing gain, more stages were required in order to achieve the proper overall open-loop gain required. It should be noted that, had time permitted, additional effort should have been expended in further refining the signal-to-noise ratio of the amplifier cascade.

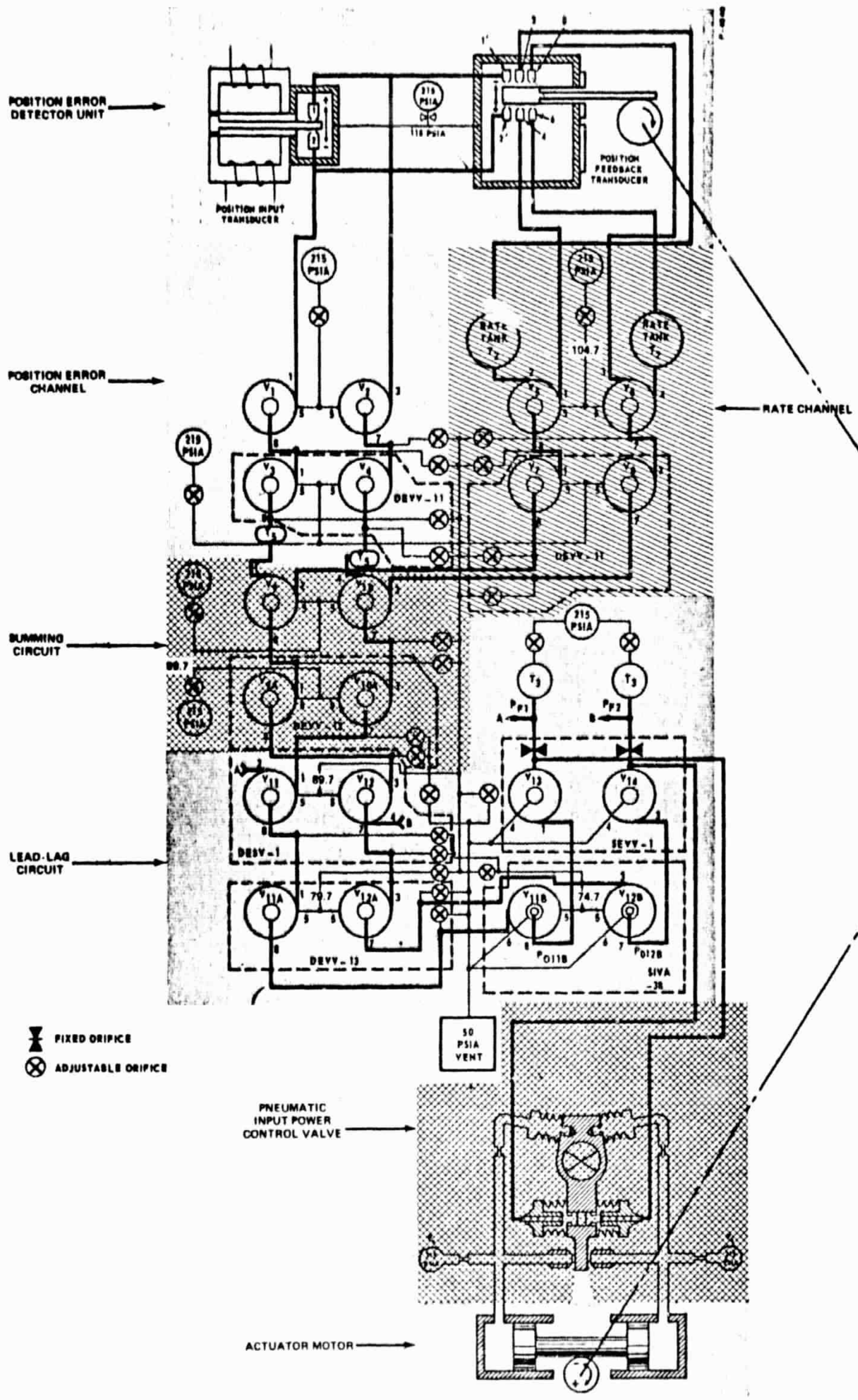


Figure 4-1 - Schematic Diagram of the Flueric Control Drum Actuation System Showing Operating Pressures

The active components consisted of vortex amplifiers (two types) and summers. The two types of amplifiers are: the vortex valve which is a flow turndown device; and the vortex valve used in conjunction with an exit flow pickoff and referred to as a pressure amplifier. The various active components and their design features are discussed in detail in Section 5. These components were designed and tested in their final configuration for every stage of the flueric amplifier circuit. The components were successfully staged to make up all of the subcircuits. A complete flueric circuit, with the exception of the rate channel, was tested.

Referring to the flueric schematic in Figure 4-1, all operating pressure levels are shown. Note that it was possible to operate each push-pull stage of the amplifier chain with a relatively low overall pressure drop, on the order of 5 to 10 psi.

4.1 POSITION ERROR CHANNEL

The position error signal enters the position error channel, which is made up of two stages of push-pull vortex valves, and performs an amplification and saturation function. Figure 4-2 is a schematic of this position error channel.

Supply pressure to valves V_3 and V_4 sets the upper pressure saturation limit while the supply pressure to the load stage summing valves, V_9 and V_{10}, sets a lower pressure saturation limit. This circuit proved to be very flexible in that limits can be easily adjusted by simply adjusting the supply pressures to these stages. The gain of this subcircuit was 22.5 psi/psi. Static performance curves for the subcircuit are shown in Figure 4-3. Differential limits were set to approximately ± 3 psi.

The lag network required to offset the lag used in the rate channel is made up by using the volumes T_5. These volumes, acting in conjunction with the input impedance of the summing amplifier, provide the proper time constant.

4.2 SUMMING AMPLIFIER

Vortex valve stages V_9 and V_{10} are used for summing the position and rate signals. Stages V_{9A} and V_{10A} are used to amplify the summed signal. Valves V_9 and V_{10} were designed to accept the full range signals from the error and rate channel without degradation of linearity; therefore, the stage gain for V_9 and V_{10} is low. These stages are shown added to the position error channel in Figure 4-4. Gain curves for these stages are shown in Figure 4-5, and indicate a position error channel gain of 0.30 psi/psi and a rate gain of 0.67 psi/psi. Linearity in the rate channel is not as critical as that for the position channel.

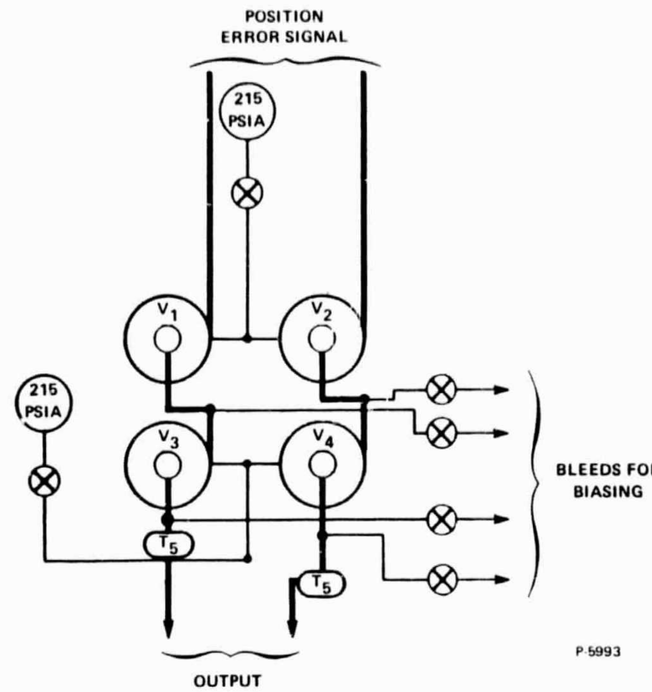


Figure 4-2 - Position Error Channel

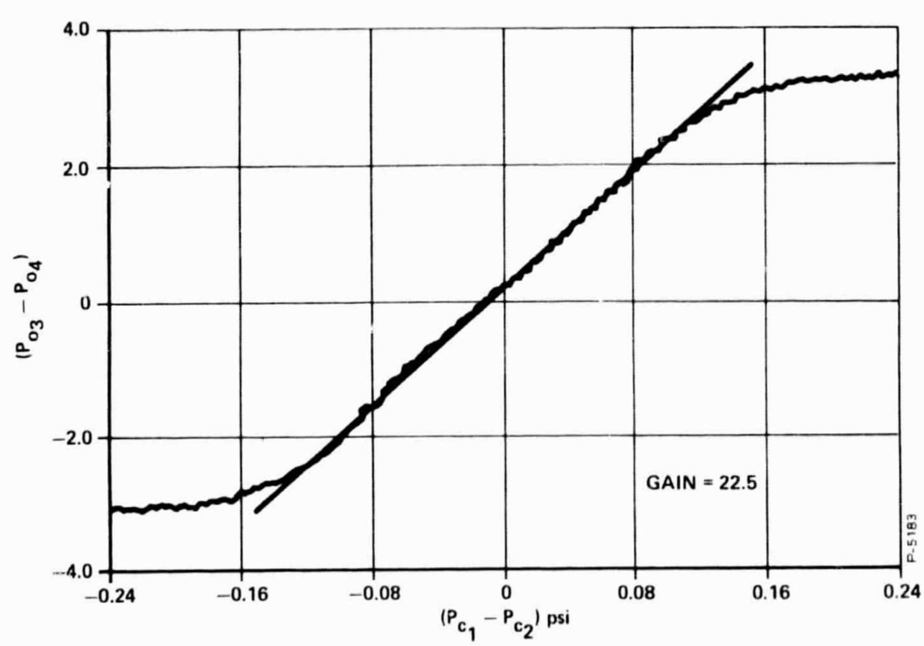


Figure 4-3 - Static Performance Characteristics of the
Position Error Channel

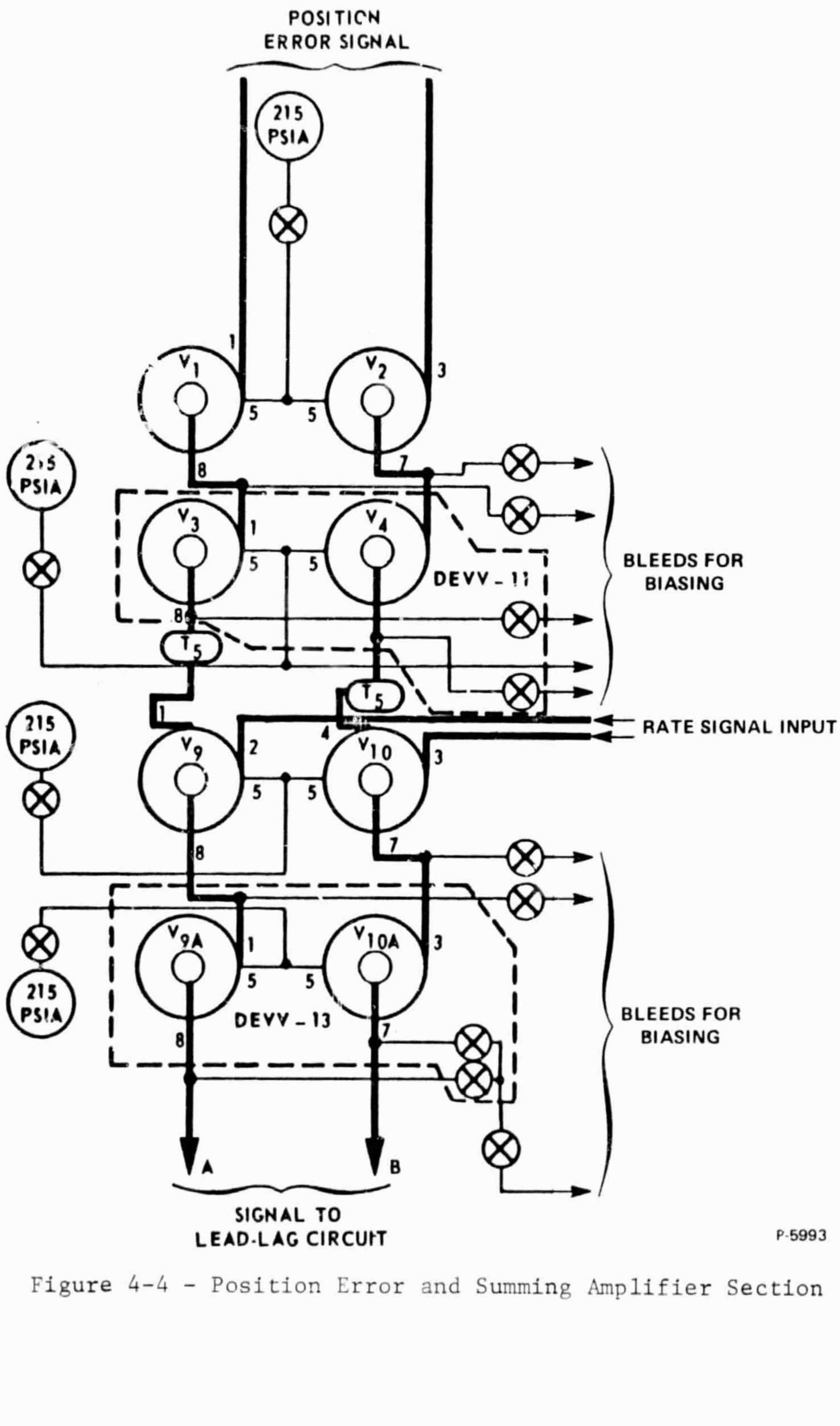


Figure 4-4 - Position Error and Summing Amplifier Section

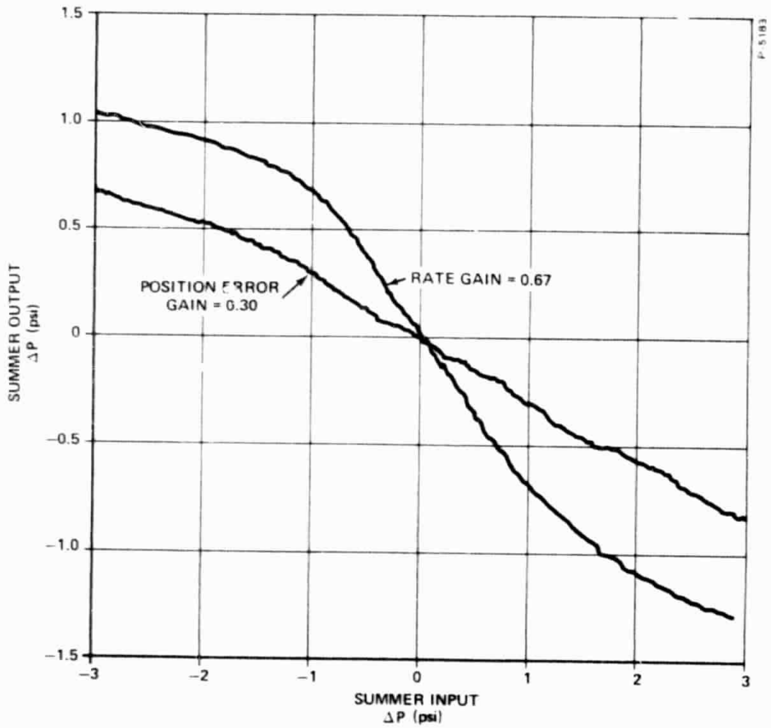


Figure 4-5 - V_9 and V_{10} Stage Static Performance Characteristics

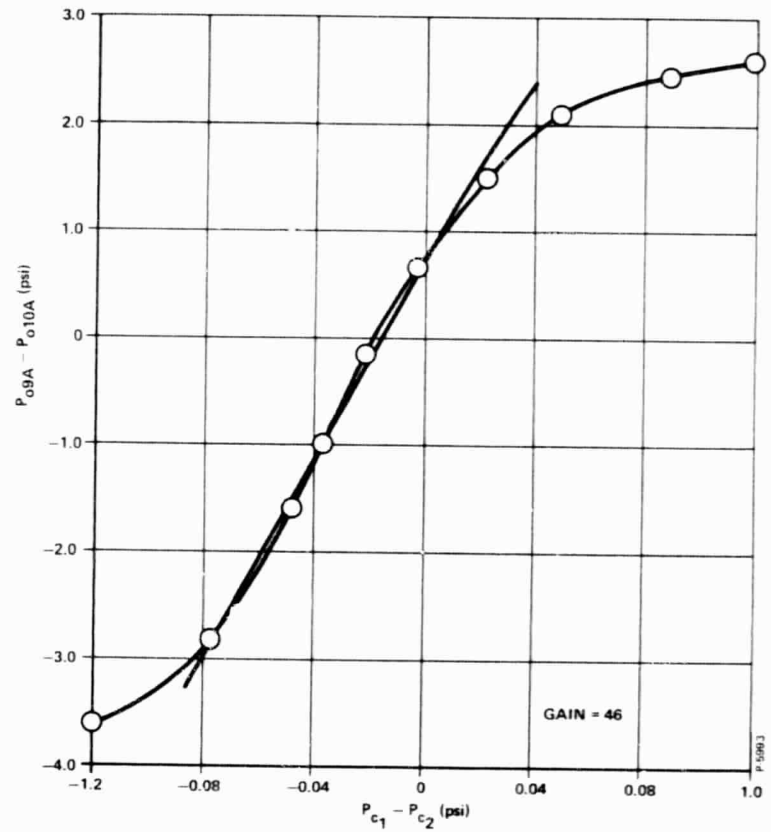


Figure 4-6 - Static Performance Characteristics of the Position Error and Summing Circuit

The position error circuit and summing amplifier, including stages V_{9A} and V_{10A}, were connected; an overall gain curve is shown in Figure 4-6. The gain was 46 psi/psi. The data in Figure 4-6 were taken before the bleeds were adjusted to center the operation of the stage. Bleeds, of course, were not finally adjusted until the rate signals had been summed at V_9 and V_{10}.

4.3 RATE CHANNEL

The rate channel is composed of two stages of push-pull vortex valves which provide differentiation of the position signal and further amplification of the signal. The schematic of the stages is shown in Figure 4-7.

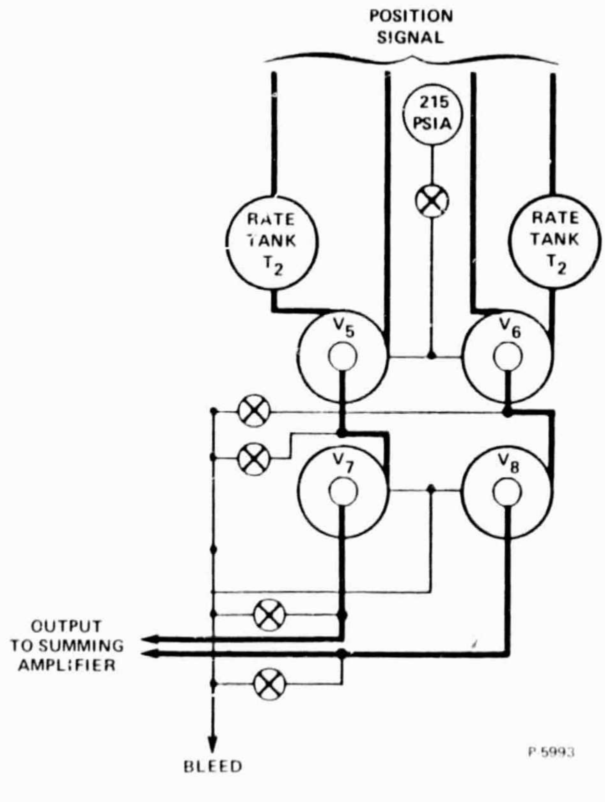


Figure 4-7 - Rate Channel Amplifier

Tanks T_2 provide lags which are used to obtain differentiation of the position signal. The more common schematic for a differentiation circuit is shown in Figure 4-8, where opposing control jets are used.

The orifice and control jets at the vortex valve are adjusted so that statically no signal change is possible. Because of tank, T_2, the input rate-of-change will cause an output.

Where signals can get large, there could be an inadvertent change in the bias direction of the valve, a condition which cannot be tolerated. To avoid this situation and to avoid a separate bias supply, the opposing signal is derived at the position sensor so that both signals can be summed in the same direction on the vortex valves V_5 and V_6, as shown in Figure 4-7.

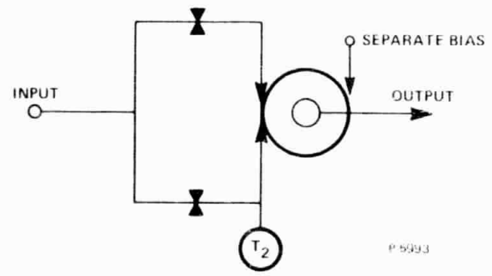


Figure 4-8 - Common Differentiation Circuit

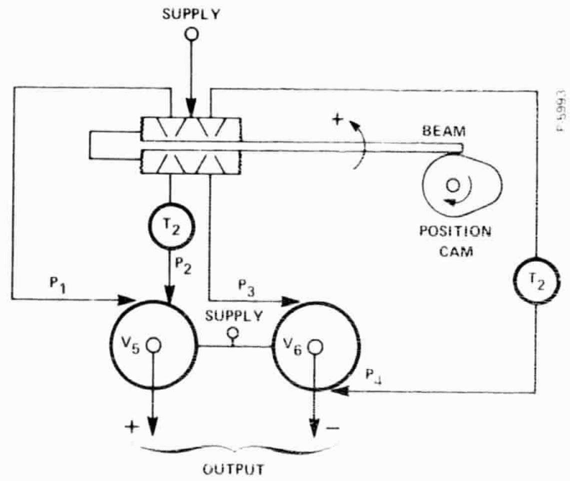


Figure 4-9 - Differentiating Circuit Using Opposing Position Signals

The differential signal is derived from the position sensor through the use of a differential nozzle pickoff. This connection is shown in Figure 4-9. Note that two pair of in-flowing position sensing nozzles are used; thus isolation orifices are not needed and a higher gain is achieved. If the beam is deflected in an upwards direction (+), then control pressure P_1 will decrease rapidly while control pressure P_2 increases at a slower rate, due to the lag caused by tank T_2. The output flow of valve V_5 will therefore increase. Valve V_6 works the opposite so that flow decreases.

The differential flow change is proportional to the derivative of the position signal.

The differentiation is easily seen by stating that if the gain of vortex valve V_5 is K_5 lb/sec/psi, for a given pressure change at ports 1 and 2, then the net output flow is given by:

$$\Delta W_5 = -K_5 \left[\Delta P_1 - \frac{\Delta P_2}{1 + s\,T_2}\right]$$

where

$$-\Delta P_1 = \Delta P_2 = -\Delta P \text{ (steady state).}$$

so that:

$$\Delta W_5 = \frac{K_5\, s\, T_2\, \Delta P}{1 + s\,T_2}$$

Care must be taken to make $\Delta P_1 = \Delta P_2$ so that the signal in the rate channel would be insensitive to position changes, otherwise this would change the calibration of the closed loop gain; i.e., the position out versus that commanded. The use of the push-pull circuit helps eliminate this problem, for if ΔP_1 were slightly greater than ΔP_2, then it is likely that ΔP_4 would be greater than ΔP_3. The effect then would cancel out in the push-pull stage, if V_5 and V_6 were matched.

The differentiated signal is further amplified by stages V_7 and V_8. The gain of the rate circuit, including the summing amplifier V_9, V_{10}, V_{9A} and V_{10A}, is shown in Figure 4-10 with the input signals to each stage adding and the T_2 tanks disconnected. The gain of this circuit is 95 psi/psi.

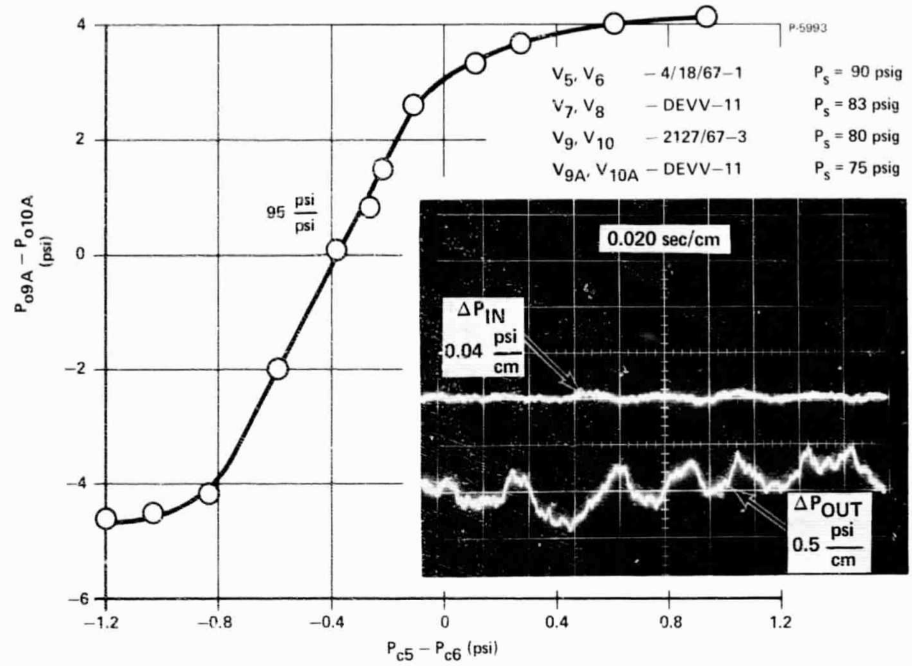


Figure 4-10 - Static Performance Characteristics of the Rate and Summing Circuit

4.4 LEAD-LAG CIRCUIT FOR ERROR RATE COMPENSATION

The lead-lag circuit is composed of two push-pull stages of vortex valves (V_{11}, V_{11A}, V_{12}, and V_{12A}) followed by a push-pull stage of vortex pressure amplifiers (V_{11B} and V_{12B}) which use the external type of pickoff. The output of the vortex pressure amplifiers drives the differential bellows actuator on the power valve and also provides the feedback signals which are passed through a lag network to provide the required lead-lag compensation. The lag-network and feedback circuit is a pressure-follower type of circuit utilizing orifices and volumes, T_3, and a pair of vortex valves V_{13} and V_{14}. The schematic of the lead-lag circuit is shown in Figure 4-11.

The vortex valve amplifier chain provides the gain, and consists of: the V_{11}, V_{12}; V_{11A}, V_{12A}; and V_{11B}, V_{12B} stages. The final amplifiers use the pickoff to drive the bellows; the chamber exit holes are vented. The final stage which drives the bellows must be vented since the bellows are dead ended. If valves with vent orifices had been used, little gain would have been realized as the vents would have had to be relatively large in order to pass the quiescent flow needed. The quiescent flow must be larger at the final stage in order to minimize the time

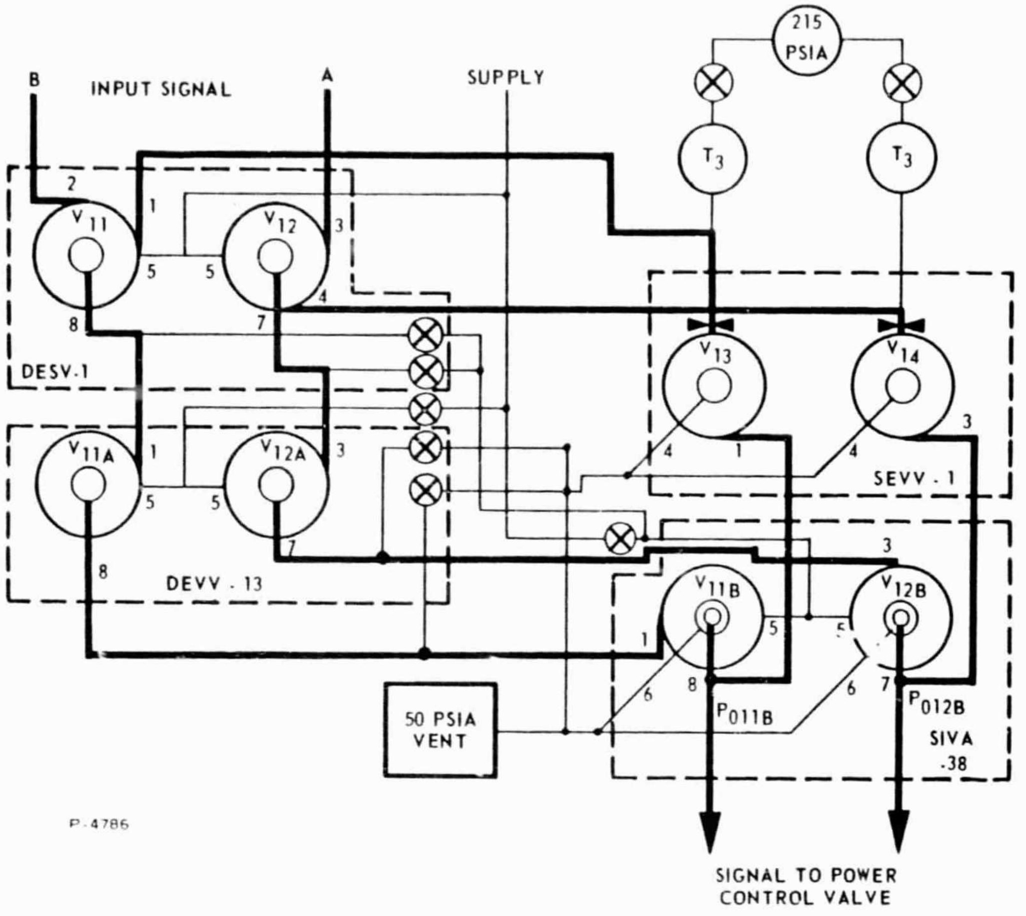


Figure 4-11 - Lead-Lag Circuit Schematic Diagram

constant resulting from having to drive the bellows system which operates the power valve. By using the pickoff amplifier, high quiescent flows are possible while maintaining excellent pressure gain. Typical gain curves for the SIVA-type amplifier, used in V_{11B} and V_{12B}, are shown and discussed in Section 5.

The pressure-follower type of feedback circuit is required in order to transfer the signal information from a nominal pressure level of 65 psia to a nominal level of 90 psia so that the signal can be injected at vortex valves V_{11} and V_{12}. It will be recalled that control pressures must be higher than the supply pressure on a vortex valve. A simplified pressure-follower circuit is shown in Figure 4-12.

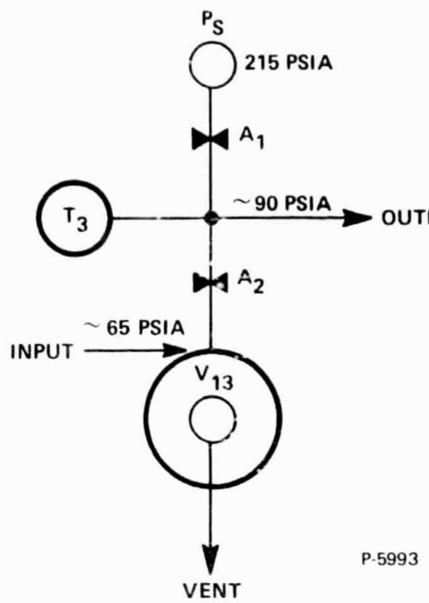


Figure 4-12 - Simplified Pressure Follower Lag Circuit

Disregarding T_3 for the moment, valve V_{13} acts as a variable orifice which changes resistance with the value of the input signal. Orifices A_1 and A_2 are selected to provide the proper operating quiescent pressure levels at the input and output connections, nominally 65 psia and 90 psia, respectively. As the input signal is raised, the impedance of V_{13} increases and the flow through A_1, A_2, and V_{13} decreases. The pressure at the output increases and, thus, the information is transferred from the 65 psia level to the 90 psia level so that it can be fed back to vortex valve V_{11}. The gain of the pressure-follower circuit was approximately 0.1 psi/psi.

Since a lead-lag compensated amplifier is desired, volume T_3 is inserted to provide the proper lag in the feedback path. The break frequency of the lag network becomes the break frequency for the lead effect when the loop is closed. At very high frequencies, volume T_3 suppresses all of the signal and the feedback path is virtually open so that the closed-loop gain equals the open-loop gain of the amplifier. Proper sizing of orifices A_1, A_2, and valve V_{13} provides the required static low-frequency gain so that the proper span in lead is accomplished.

The lead-lag circuit has met the required static gain, pressure swing, and dynamic performance characteristics.

The lead-lag circuit static performance characteristics are shown in Figure 4-13. Open-loop and closed-loop gain are both shown in this figure. The open-loop gain is in excess of 100 psi/psi and closed-loop

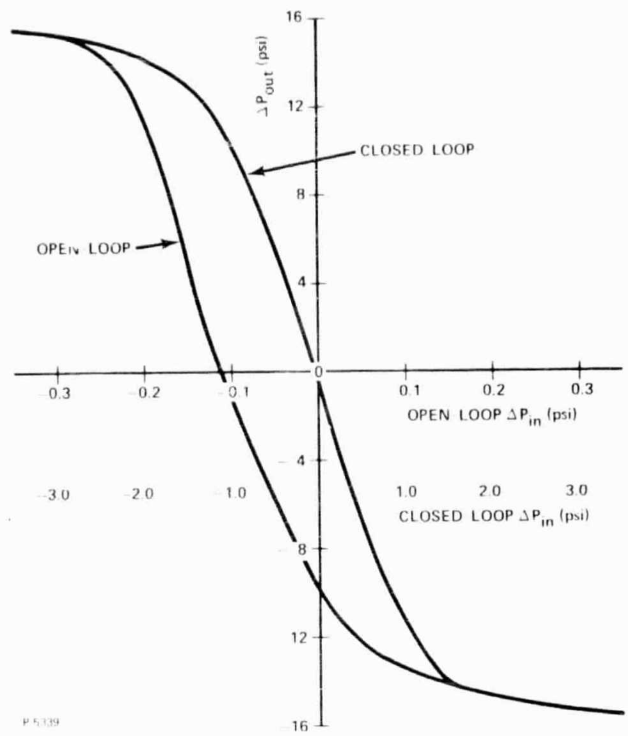


Figure 4-13 - Lead-Lag Circuit Static Characteristics

gain is about 12 psi/psi. The output swing is about $\pm$15.5 psid. Earlier design calculations show that at least $\pm$12 psid would be required to drive the power control valve.

In dynamic tests of a lead-lag circuit, it was established that its dynamic characteristics were substantially affected by the load volumes anticipated in the original design. Frequency response data were obtained with three different load volumes. The first frequency response curve, shown in Figure 4-14, was obtained with a load volume equivalent to that of the original design. Figure 4-15 presents the frequency response obtained with a load volume that represents the lead-lag circuit mounted directly on the power control valve. The frequency response shown in Figure 4-16 was obtained with only the instrumentation volume as a load volume.

The desired phase lead was achieved in the second configuration by decreasing the load volume by approximately a factor of three, and by increasing T_3 from 0.22 in^3 to 0.32 in^3.

To accomplish the load volume reduction, plans were made to mount the lead-lag circuit directly on the power valve.

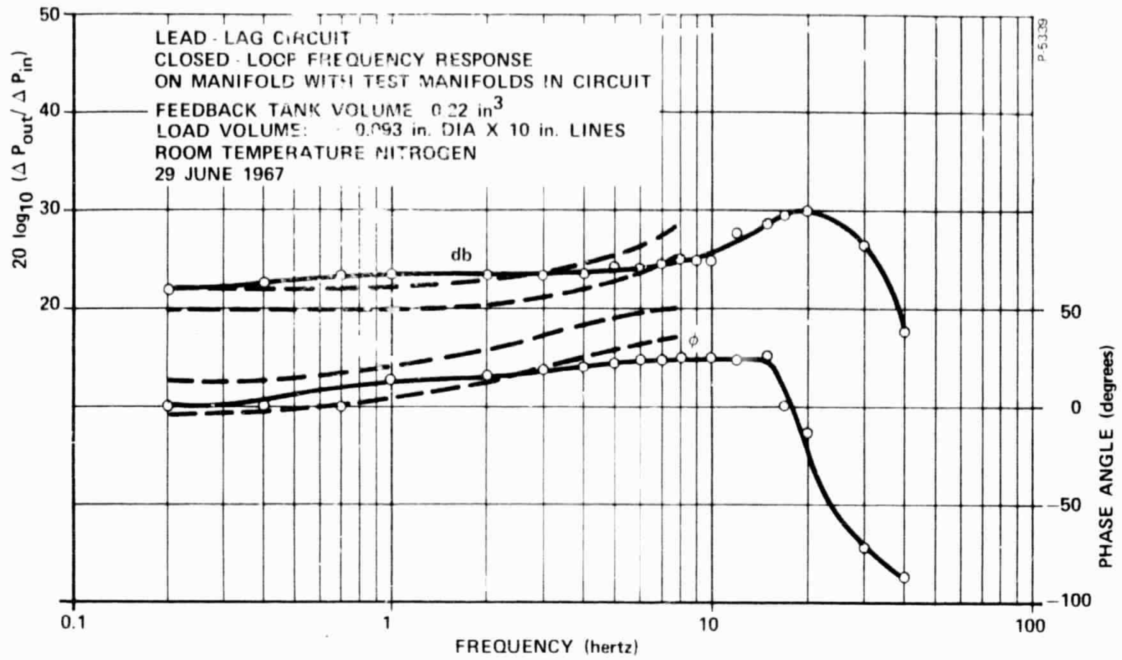


Figure 4-14 - Lead-Lag Frequency Response Characteristics with Originally Designed Output Volume

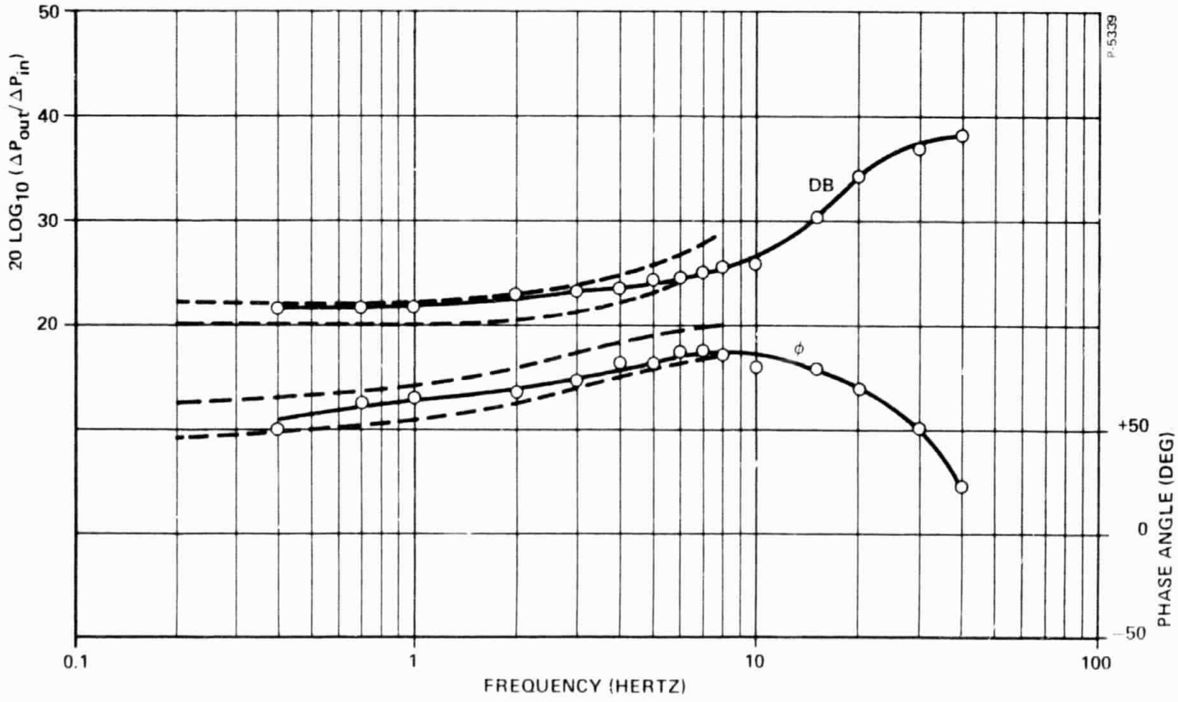


Figure 4-15 - Lead-Lag Circuit Frequency Response Characteristics-Output Volume Represents Lead-Lag Circuit Mounted Directly on Power Control Valve

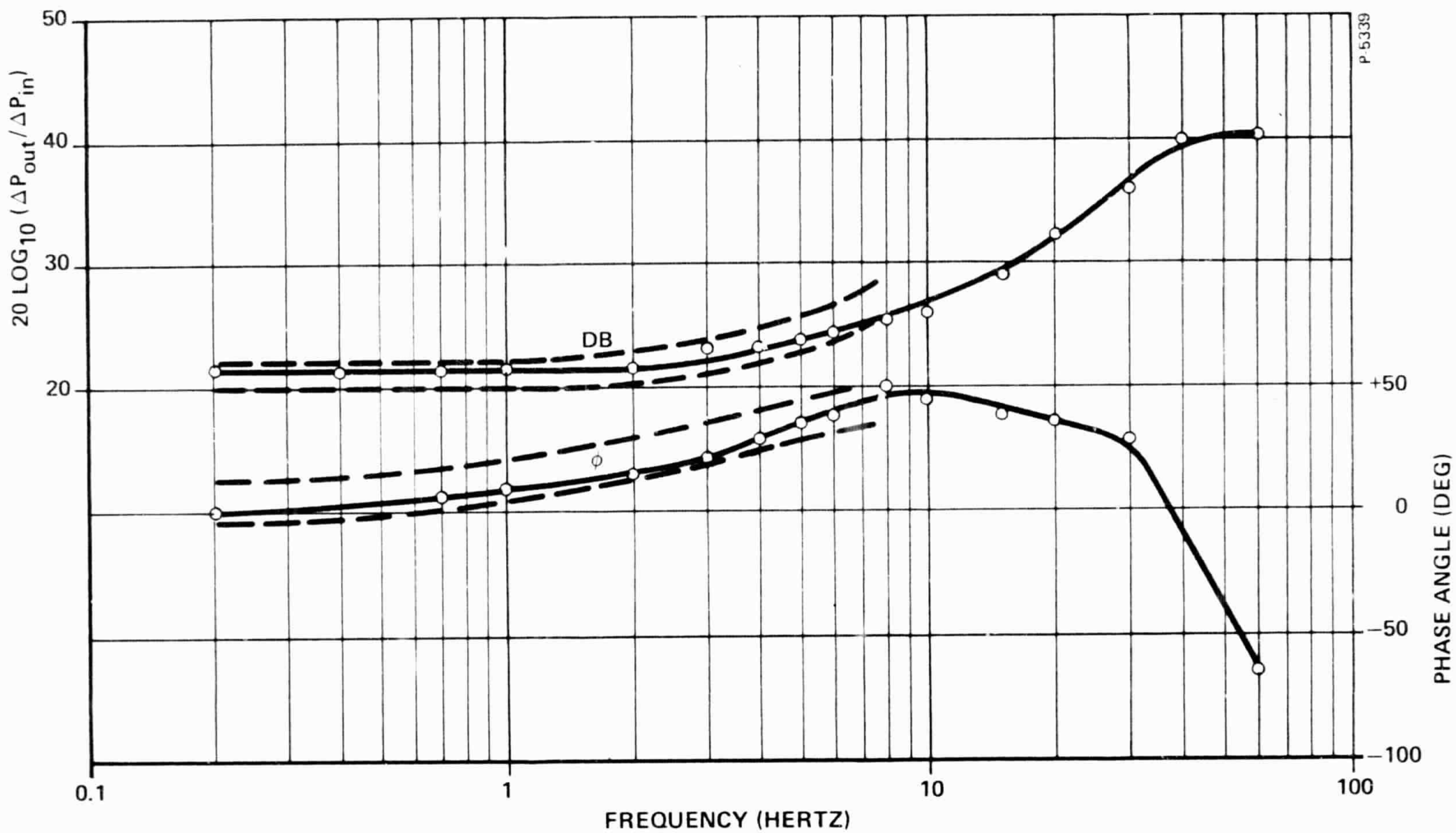


Figure 4-16 - Lead-Lag Circuit Frequency Response Characteristics Output Volume Limited to Instrumentation Volume Only

SECTION 5

VORTEX COMPONENTS

Two types of vortex amplifiers and a vortex summer are used to implement the flueric amplifier circuit. The two types of amplifiers are: the vortex valve which is a basic vortex element and a flow turn-down device; and the vortex pressure amplifier which uses a basic vortex valve and a pickoff or receiver in the exit flow stream of the vortex valve. The summer is essentially a vortex valve with multiple inputs and, for this application, is designed to have very low gains. The vortex elements used in the flueric amplifier circuit are small in size having a chamber diameter of 0.140 inch and an exit orifice diameter of 0.020 inch.

The operational theory of the various vortex elements, their design and construction, and the operating characteristics of the particular elements used in this application are described in this section.

5.1 THEORY OF OPERATION

The basic vortex valve consists of a cylindrical chamber with supply flow and control flow inlets, and an outlet orifice as illustrated in Figure 5-1. The supply flow of gas enters the chamber and, in the absence of control flow as indicated in Figure 5-1(a), proceeds radially inward, without resistance, and then flows out of the outlet orifice. In the absence of control flow, the maximum total flow through the valve is achieved with the main pressure drop occurring across the output orifice. The chamber pressure is slightly less than the supply pressure. Control flow at pressure above chamber pressure is injected tangentially into the chamber, as shown in Figure 5-1(b). The tangential control flow imparts a rotational component to the supply flow. The combined flow has a tangential and a radial component. Conservation of momentum requires that the tangential velocity and the radial velocity both increase as the flow moves inward. Centrifugal force, due to the fluid rotation, results in

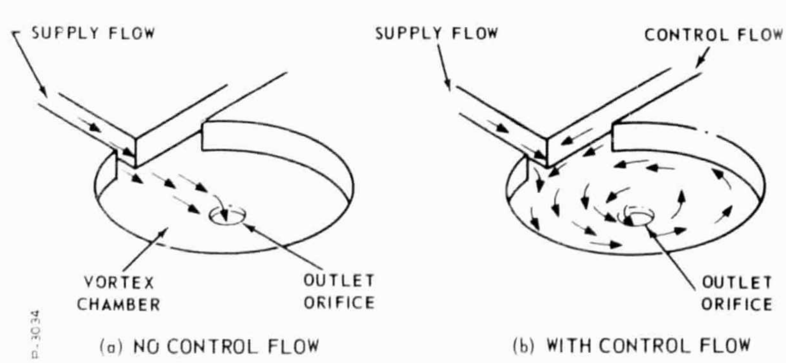


Figure 5-1 - Vortex Valve

a radial pressure gradient. For a constant supply pressure, this drop in pressure across the chamber reduces the pressure differential across the outlet orifice, and thus reduces the outlet flow.

A reduction in the total outlet flow as high as 7:1 has been achieved with vortex valves. At the lowest outlet flow, the supply flow to the valve is virtually zero. At this point, the outlet flow is being supplied almost entirely by the control flow.

The schematic symbol of the vortex valve is shown in Figure 5-2. In this figure, P_V is the pressure downstream of the vent orifice. P_c is the control pressure, and P_s is the supply pressure.

A vortex pressure amplifier is similar to a vortex valve with the exception that a pickoff or receiver is placed in the gas stream of the outlet orifice; the pickoff acts in much the same manner as a pitot tube. The receiver pressure and flow is the output of the device. When there is no control flow, the flow out of the outlet orifice is directed into the receiver, Figure 5-3(a) and the pressure and flow recovered under the condition is at a maximum. As control flow is added, the exit flow fans out as shown in Figure 5-3(b), and the recovered pressure decreases. Hence, the vortex pressure amplifier uses the combined effects of vortex valve and flow diversion for obtaining amplification.

The pickoff is capable of supplying a significant amount of flow with some decrease in pickoff output pressure but very little loss in total available pressure change or in the available increment of change of output pressure versus control pressure. That is to say, the pressure gain is nearly constant for a wide range of load impedance. Figures 5-4 and 5-5 are examples of performance of the 0.25-inch chamber diameter vortex pressure amplifier. The weight flows shown are for nitrogen. On hydrogen, the blocked load pressures will be virtually identical but, of course, the weight flow scale will change. The schematic symbol for the vortex pressure amplifier is shown in Figure 5-6.

As with the vortex valve, P_s is the supply pressure, P_c is the control pressure, and P_V is the pressure downstream of the vent orifice. P_o is pickoff or receiver pressure.

A summer is a basic vortex valve, or pressure amplifier, with multiple control flow inlets to which different control signals may be introduced, as shown in Figure 5-7. In this application all summers were vortex valves.

The schematic for the summer is shown in Figure 5-8.

5.2 CONSTRUCTION

The vortex components were fabricated by means of a metal-etching and diffusion-bonding technique. All of the component flow passages, including manifolding and the vortex chambers, are etched through thin metal discs. These discs are then stacked together to provide the proper channel depth and channel communication.

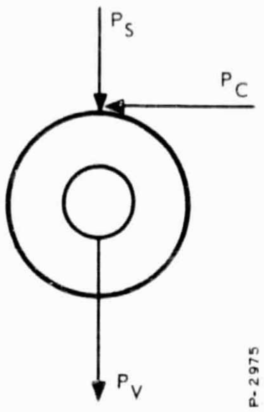


Figure 5-2 - Schematic Symbol of Vortex Valve

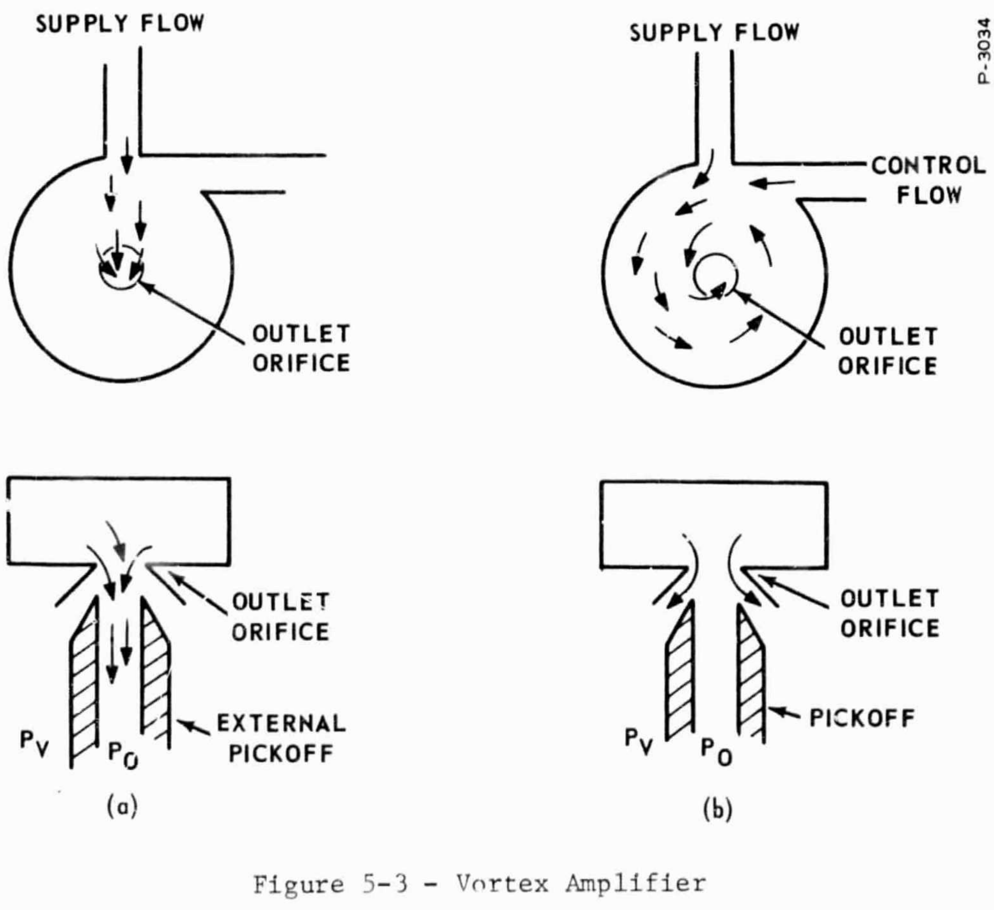


Figure 5-3 - Vortex Amplifier

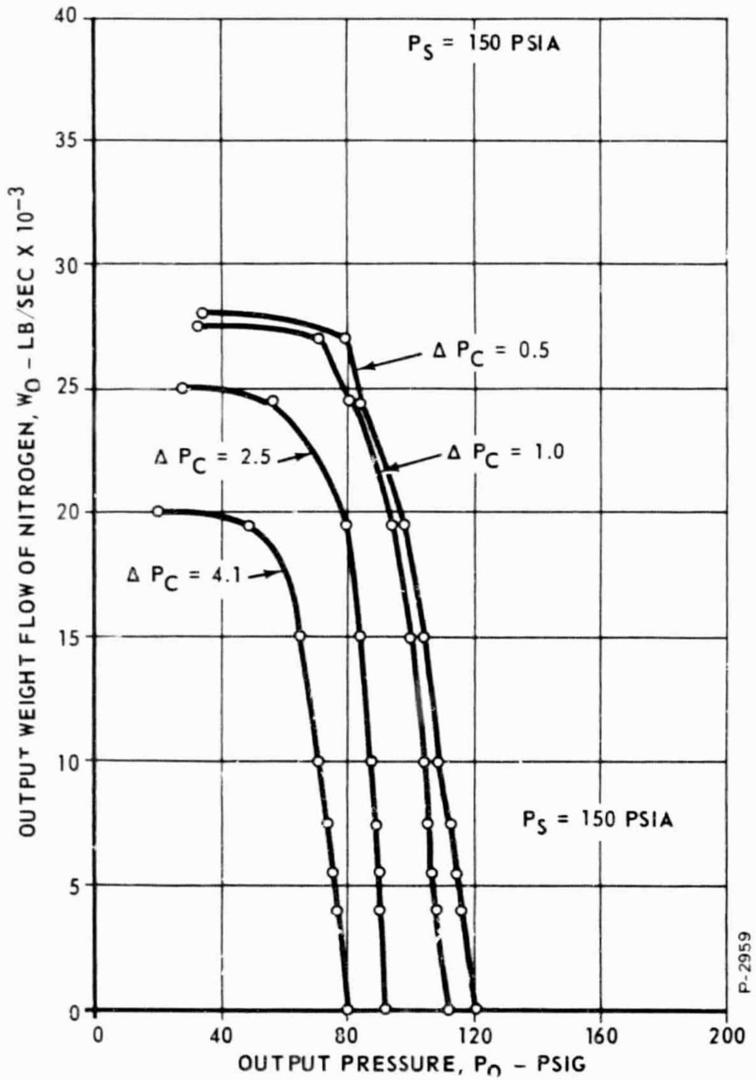


Figure 5-4 - Load Flow Versus Load Pressure for Typical Vortex Pressure Amplifier

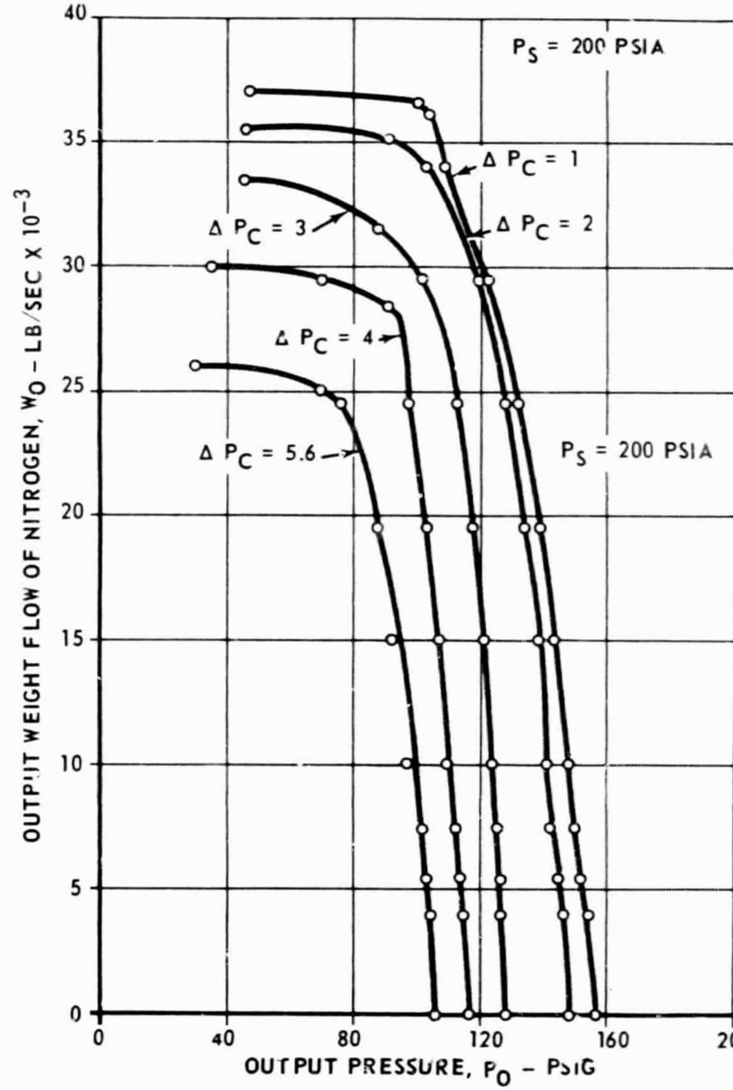


Figure 5-5 - Load Flow Versus Load Pressure for Typical Vortex Pressure Amplifier

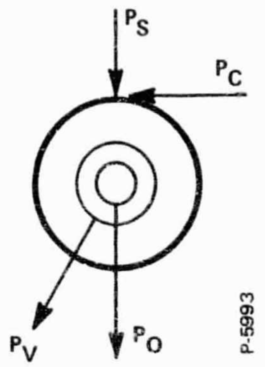


Figure 5-6 - Schematic Symbol of Vortex Pressure Amplifier

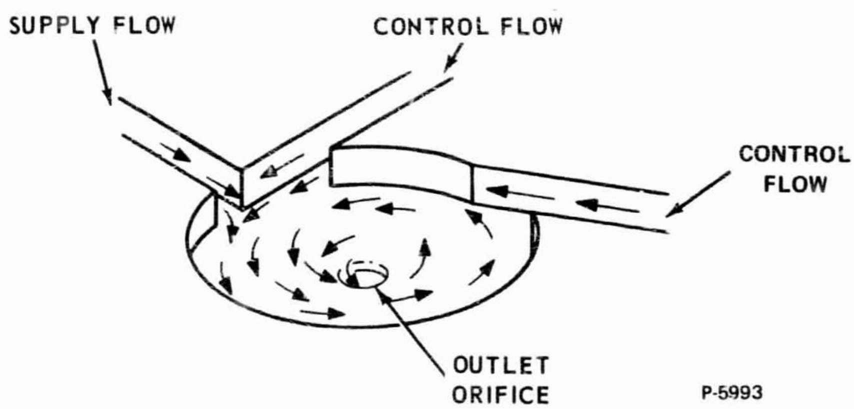


Figure 5-7 - Vortex Summer

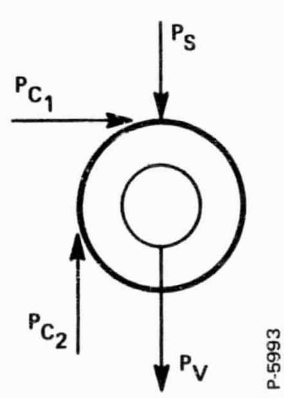


Figure 5-8 - Schematic of Vortex Summer

The vortex components are initially designed and tested by bolting the discs to a test block and checking the performance characteristics. When the desired characteristics are attained, the stack of discs is then diffusion bonded into a push-pull vortex component stage.

The plan view of a summer, illustrating how passage chambers are etched into the disc and then stacked, is shown in Figure 5-9. The cross section of the vortex pressure amplifier used in the system is shown in Figure 5-10. A photograph of integrated push-pull stages of a summer and vortex pressure amplifier are shown in Figure 5-11.

5.3 CHARACTERISTICS

The static performance characteristics of the vortex elements, used in the flueric amplifier circuit, are presented in this section. The dynamic characteristics of the individual vortex elements were found to be extremely difficult to determine; the volumes of the passages, associated with instrumentation used, mask out their actual characteristics. The high response of the small elements used is demonstrated by the dynamic characteristics of the forward-path, lead-lag circuit. The schematic of the circuit is shown in Figure 5-12, and the frequency response characteristics, in Figure 5-13.

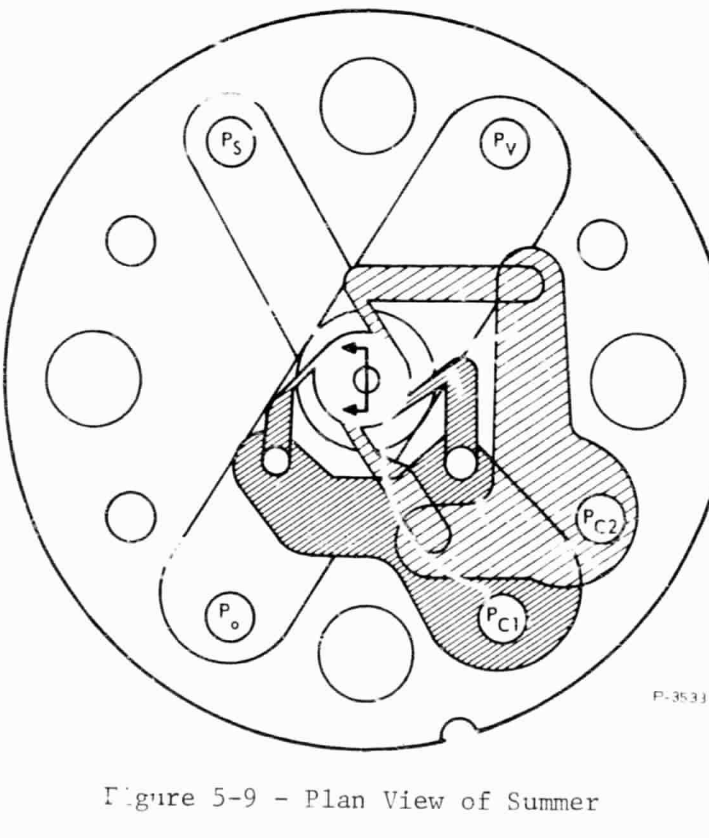


Figure 5-9 - Plan View of Summer

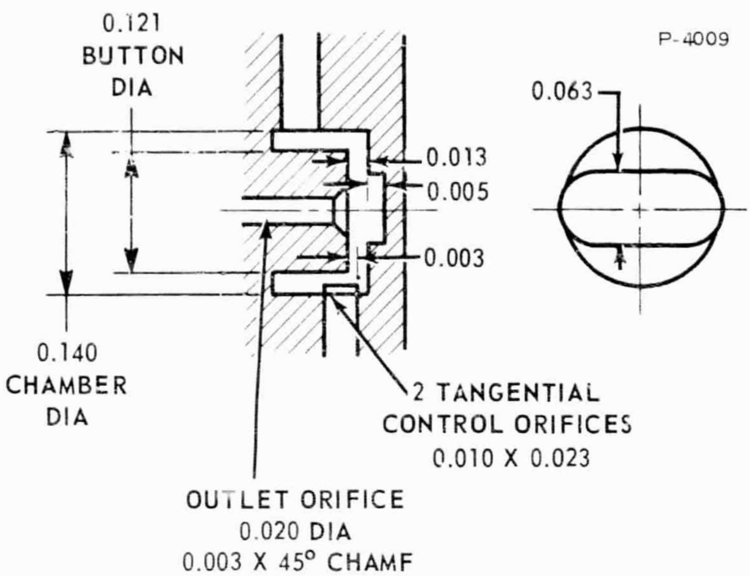


Figure 5-10 - Cross Section of Vortex Pressure Amplifier

Figure 5-11 - Integrated Push-Pull Stage of Low Gain Summer and Single Input Vortex Pressure Amplifier

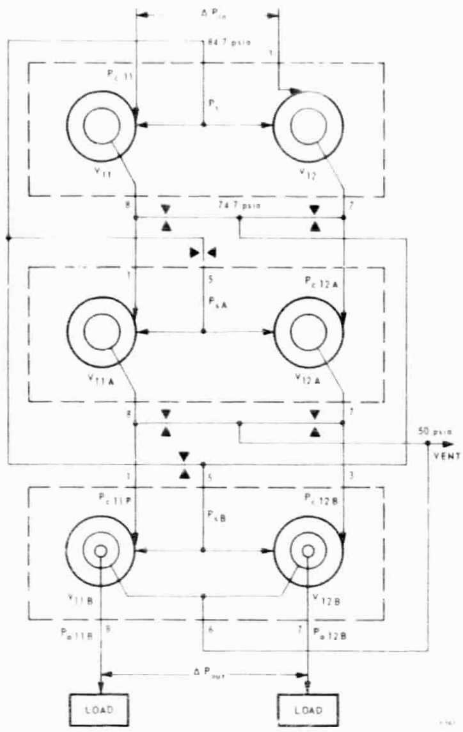


Figure 5-12 - Schematic of Forward Path of Lead-Lag Circuit

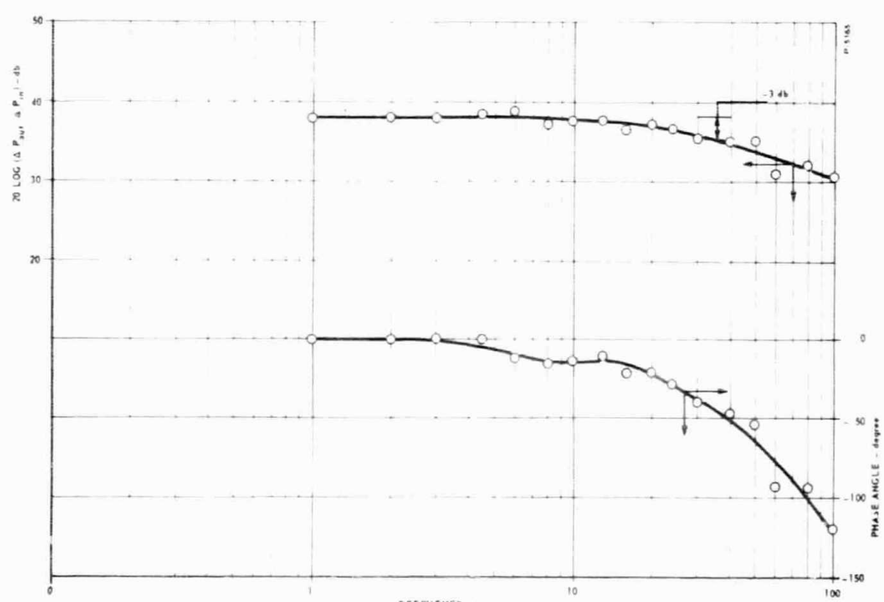


Figure 5-13 - Frequency Response of Forward Path of Lead-Lag Circuit

5.3.1 Pressure Amplifier

A vortex pressure amplifier was used in output stage of the lead-lag circuit. Its output was the input signal to the power control valve.

The output load-flow curves and input impedance curves for the dual pressure amplifier stage, V_{11B} and V_{12B}, of the lead-lag circuit, are presented in Figures 5-14, 5-15 and 5-16. V_{12B} is located on top of V_{11B} in the bonded assembly. This makes the input and output passages slightly longer and introduces several added direction changes. We believe this is the reason for the observed difference in performance between V_{11B} and V_{12B}. This difference will not cause improper lead-lag circuit operation.

Note the slight fold-over of the flow curves in Figure 5-14. The curve for ($P_c - P_s = -1$) is to the left of the curve for ($P_c - P_s = -0.6$). This is negative or reverse turndown of the vortex flow. We believe this is due to the supply manifold. The V_{12B} stage, where the details of the supply manifold are different, has never shown this effect. In the push-pull circuit, with a shared supply port, the reverse turndown effect is fully suppressed and, thus, will not be a problem in this application.

5.3.2 Valve

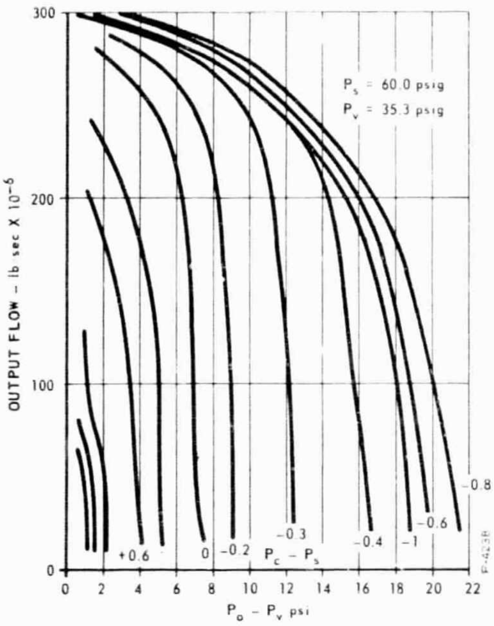
The double exit vortex valve (DEVV) is used in all the stages of the flueric amplifier circuit with the exception of the summer stages and the output stages of the lead-lag circuit. The use of a double exit on the valve results in a higher turndown ratio with the same package size. A cross section of a double exit is shown in Figure 5-17.

The flow turndown characteristics of the vortex valves used in the flueric amplifier circuit are shown in Figure 5-18.

5.3.3 Summers

Construction of a low gain summer is similar to any other vortex valve, except that it has two control signal inputs, each feeding two injector slots (see Figure 5-9). All four injector slots are the same size, and on the same level, so that effects are very closely matched.

The flow turndown characteristics of the summer are shown in Figure 5-19.



gure 5-14 - Loading Characteristics of Lower Section of Vortex Pressure Amplifier Type SIVA-38

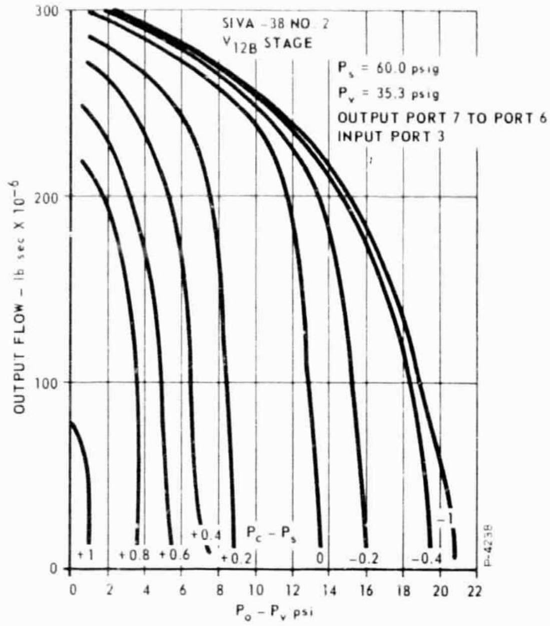


Figure 5-15 - Loading Characteristics of Upper Section of Vortex Pressure Amplifier Type SIVA-38

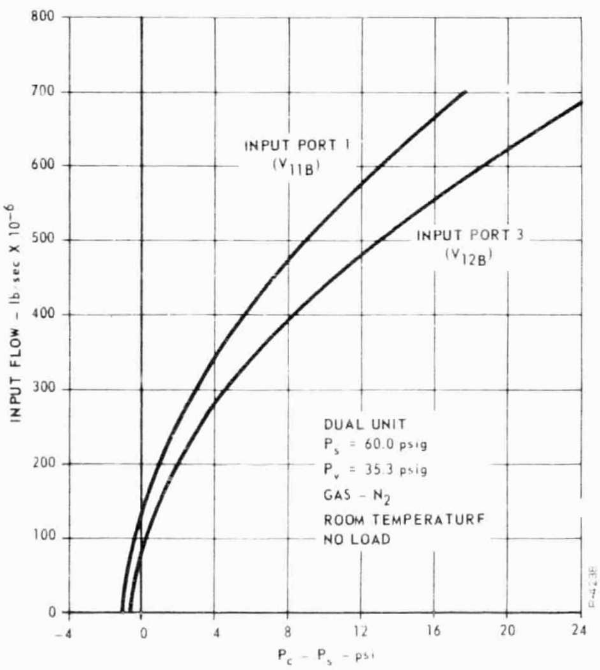


Figure 5-16 - Input Impedance Characteristics of Vortex Pressure Amplifier Type SIVA-38

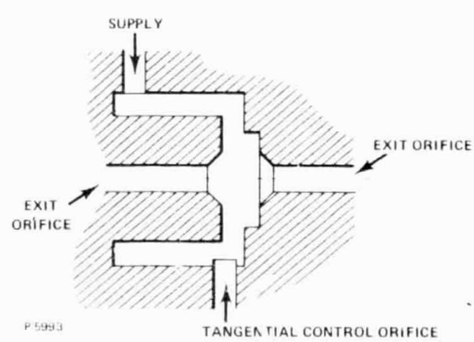


Figure 5-17 - Cross Section Double Exit Vortex Valve

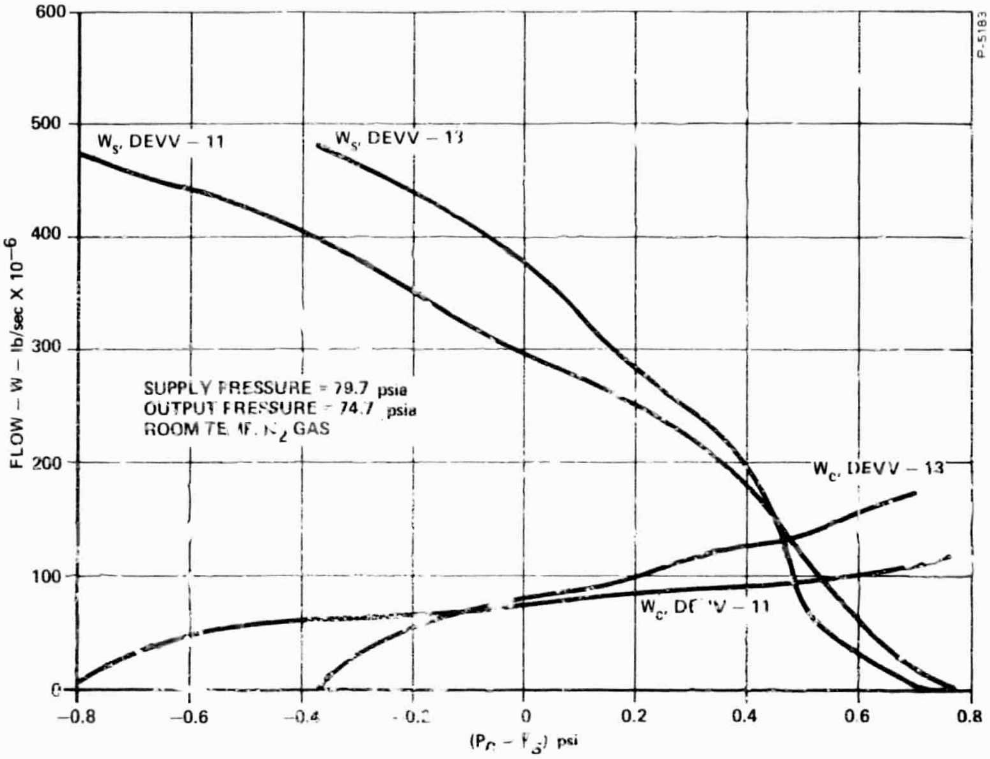


Figure 5-18 - Vortex Valve Stat'c Flow Characteristics

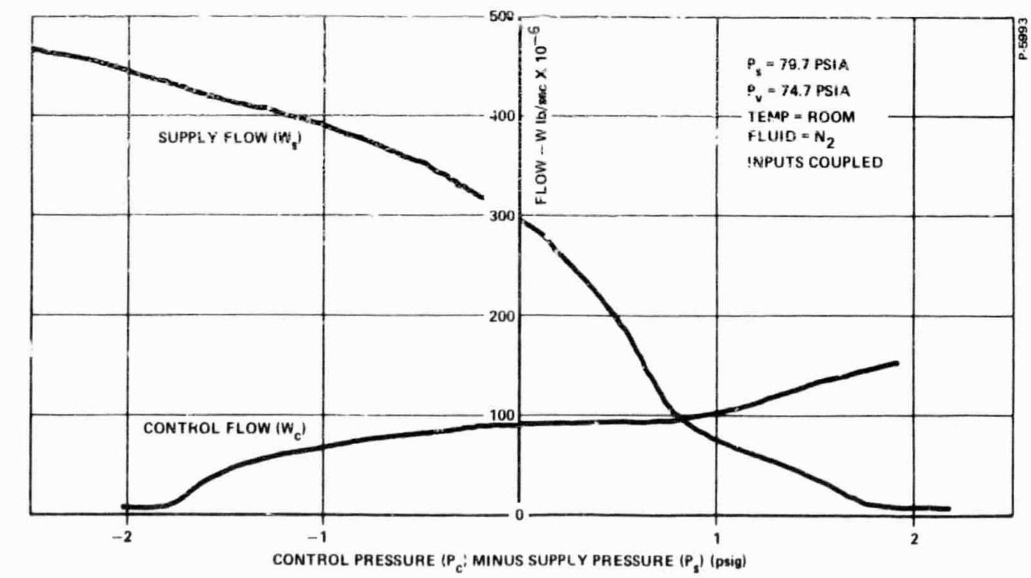


Figure 5-19 - Vortex Valve (DESV-1) Static Flow Characteristics

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

The objective of this effort was to design, fabricate, and evaluate a flueric position servo. An actuator-motor was prescribed, which required a sophisticated compensation and amplification network to meet performance requirements.

In Task I a system was designed and analytically studied. The study concluded that: the designed flueric position servo would have desired performance capabilities and a low gas consumption; the flueric amplifier network would be compact and readily mounted on the actuator; and the vortex devices used in the design would have required performance capabilities.

6.1 CONCLUSIONS

In Task I, the static and dynamic performance characteristics of each circuit of the flueric network were defined. The most complex circuit of the network was the lead-lag circuit which incorporated all the types of vortex components used in the flueric amplifier network. Contained in the circuit were a summer stage, an amplifier stage, a pressure follower feedback stage, and an output stage using a pressure amplifier. This circuit was experimentally evaluated in its final configuration using nitrogen gas and it demonstrated that it can meet defined requirements. In meeting defined requirements, the possibility was established that vortex elements could be staged in push-pull pairs. Also found possible was that: vent flow of an upper stage could supplement the supply flow of a lower stage; required gains can be achieved; vortex components have sufficient dynamic response; and the physical configuration of this circuit was a compact integrated package.

The other portions of the flueric circuit were breadboarded and evaluated experimentally, and they demonstrated a capability in achieving required static characteristics.

Developmental and evaluation tests of components and circuits revealed that the signal-to-noise ratio was higher than originally predicted. A significant amount of effort was expended in reducing noise levels. The signal-to-noise ratio, in the lead-lag circuit and other portions of the circuit, was reduced to an acceptable level, but was still excessive in the rate channel.

It can be concluded from the effort conducted that:

(1) It is possible to design and construct a flueric amplifier network that will meet the performance requirements specified in Task I.

(2) In its final configuration such a flueric amplifier network will be a compact integrated structure that can be easily mounted to an actuator.

(3) By demonstration, it is possible to use the vent flow of an upper push-pull stage to supplement the supply flow of a following stage, and that gas consumption of such a network will be low.

(4) Additional effort in reduction of the signal-to-noise ratio of components and circuit is essential.

6.2 RECOMMENDATIONS

All hardware for the flueric position servo has been fabricated and all of the flueric network has been designed and successfully tested with the exception of the rate channel. The rate channel has the appropriate gain but its signal-to-noise ratio is too high.

It is, therefore, recommended that, when possible, this effort be reinstated and concluded. To successfully conclude this effort, the following work still needs to be done:

(1) Reduce the noise level in the rate channel.

(2) Provide permanent adjustment bleed orifices on the push-pull stages of the flueric circuit. The bleeds have been proved but final permanent hardware designs were not possible.

(3) Test and adjust the error detector unit and power control valve.

(4) Assemble, check out, adjust, and test the complete position servo as originally planned.

(5) Work at further noise reduction, as needed, to eliminate unwanted noise at the servo output, should it occur.

APPENDIX A

REQUIREMENTS AND SPECIFICATIONS

This appendix lists the system component requirements, performance specifications, and environmental conditions under which the actuation system must operate, as specified in the contract.

A.1 SYSTEM COMPONENT REQUIREMENTS

In the analysis, all fluid interaction components used in the actuation system shall be described. The description shall contain performance calculations substantiated by sufficient experimental evidence to support the use of the proposed components.

A.1.1 Input Transducer

The input transducer shall be capable of receiving an electrical command signal and converting it to a pneumatic command signal. This shall be the only electronic component permitted in the servo system and may contain moving mechanical parts. Selection of the electro-mechanical input transducer shall be based upon the following requirements:

(a) System performance specifications shall be met without subtracting out errors, nonlinearities, etc., of the input transducer.

(b) The input transducer shall be capable of functioning under the environmental conditions described in subsection 1.3.

(c) The input transducer shall not require a driving signal larger than 20 volts at 200 milliamperes.

(d) The system static and dynamic characteristics shall be specified only in terms of voltage or only in terms of current applied to the input transducer.

A.1.2 Summing Junction

The summing junction shall be a pneumatic device with no moving parts.

A.1.3 Preamplifier and Frequency Compensator

The preamplifier and frequency compensator shall be fluid interaction devices which contain no moving mechanical parts.

A.1.4 Power Valve

The power valve shall be a pneumatic valve which may contain moving mechanical parts. It is desirable that the power valve be a fluid interaction device with no moving mechanical parts, but this is not a requirement of this investigation.

A.1.5 Actuator

The actuator shall be a General Electric AG-20 actuator-motor. The rotation of the actuator-motor output shaft shall be considered the output of the servo system. A scram spring shall be provided to drive the output shaft to zero when pneumatic power to the actuator-motor is stopped.

A.1.6 Position Transducer

The output shaft position pickoff transducer shall be a pneumatic device which may contain moving mechanical parts.

A.2 ACTUATION SYSTEM PERFORMANCE SPECIFICATIONS

A.2.1 Rated Load Characteristics

(a) Total inertia of load	92.5 lbm -in^2
(b) Load friction	32 in-lbf static 25 in-lbf dynamic
(c) Bias (scram) spring loading in direction of 0° drum rotation (± 10 in-lbf)	50 in-lbf @ 15° rotation

A.2.2 Static Performance Characteristics

(a) Travel	0° to 180° ± 1° maximum 15° to 165° ± 1° working
(b) Static position resolution at the actuator output shaft	± 0.2°

(c) Static linearity of output shaft position to electrical command signal to input transducer	± 4% of full travel (specification) ± 1% of full travel (goal)

A.2.3 Dynamic Performance Characteristics

(a) Transient response to an 18° step input	
(1) Rise time to 62.5% of step command	0.055 sec
(2) Settling time to within 0.[illegible]% of command	0.15 sec
Allowable overshoot (maximum)	6°
(b) Frequency response to a ± 2° input	
(1) Phase shift at 6 cps (maximum)	90°
(2) Phase shift at 12 cps (maximum)	180°
(3) Output shaft amplitude variation from 0 to 8 cps	Less than ± 3 db
(c) Maximum dynamic resolution at 3 degrees/sec slewing velocity	± 0.5°
(d) Maximum slewing velocity	± 300°/sec

A.2.4 Fluid Requirements

(a) Actuator power	
(1) Working fluid	Hydrogen (dry air, nitrogen, or helium or any combination of these gases may be used to

	simulate hydrogen at temperatures at/or less than 400°R, providing that the contractor offers proof that the substitution of these gases approximates the use of hydrogen at those temperatures.)
(2) Supply pressure	215 psia ± 10 psi
(3) Exhaust pressure	50 psia ± 5 psi
(4) Supply gas temperature	Arbitrary
(5) Gas consumption	0.04 lbm/sec of hydrogen at a temperature of 100°R The NRTO Project Manager shall have the option of relaxing this requirement, under certain circumstances, by permitting the flow rate to be increased to 0.075 lbm/sec of hydrogen at 100°R.

A.2.5 Operational Life

All components, except the basic G.E. AG-20 actuator-motor, shall be capable of operating continuously for at least 200 hours without breakdown when subjected to the vibration environment listed in subsection A.3.

A.3 ENVIRONMENTAL CONDITIONS

The prototype actuation system shall be capable of operation under the environmental specifications denoted by asterisk (*) in the following list. Performance under the environmental conditions preceded with a dagger (†) shall be considered as a desirable goal, that will ultimately be required for an actuation system. Therefore, no materials or components shall be selected that are inherently incompatible with this environment.

A.3.1 Environmental conditions during non-operation

(a)*	Shock along all axes	6 g's
(b)*	Vibration along axes	6 g's amplitude from 0 to 20 cps. Vibration increases linearly to 20 g's amplitude at 200 cps and remains constant up to 2000 cps.
(c)*	Acceleration	8 g's along output shaft axis 1 g normal to ouput shaft axis;
(d)‡	Ambient air pressure	Sea level to 0.5 in. Hg
(e)‡	Ambient air temperature	Room temperature to -70°F
(f)‡	Radiation field	Essentially negligible before reactor startup. Not known after reactor shutdown but

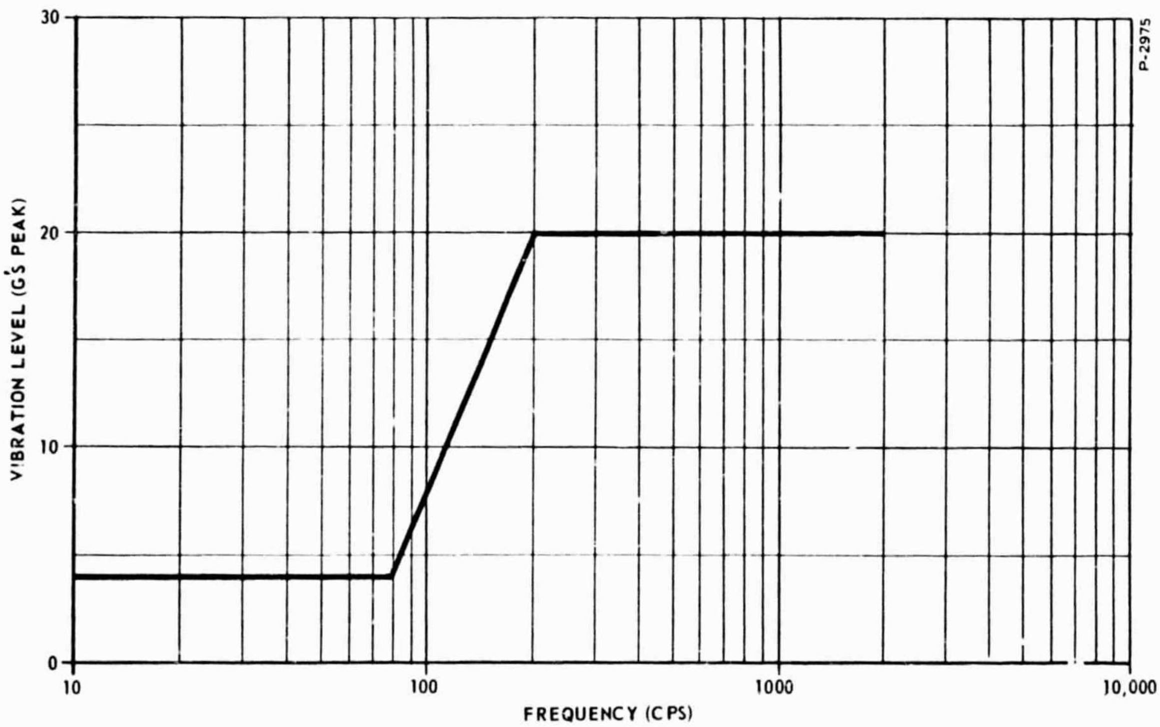


Figure A-1 - Variation of Vibration Level Versus Frequency

estimated to be small in comparison to that existing during reactor operation.

A.3.2 Environmental conditions during system operation

(a)* Shock loading	Negligible
(b)* Vibration	4 g's from 0 to 50 cps. 20 g's from 80 cps to 2000 cps (See Figure A-1).
(c)* Acceleration	1.2 g's along output shaft axis. 0.6 g's normal to output shaft axis.
(d)† Radiation field	
(1) Total dose	6×10^{6} rads (ethylene) 1 hour.
(2) Fast neutron flux rate (E 1.0 mev)	3×10^{11} neutrons/cm^2 sec
(3) Gamma heating (equivalent)	350 watts/lbm aluminum
(e)† External pressure	Less than 10^{-9} mm Hg